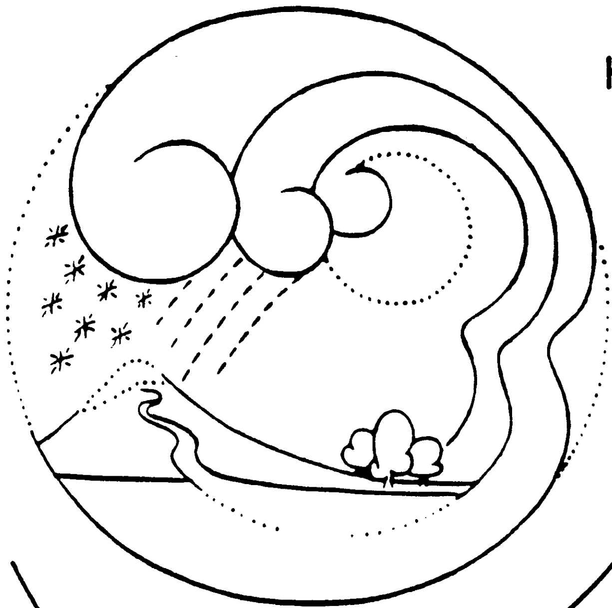

HYDRO TECHNICAL NOTE - 4

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NEXRAD TECHNICAL REQUIREMENTS FOR PRECIPITATION ESTIMATION AND ACCOMPANYING ECONOMIC BENEFITS

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by

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EXECUTIVE SUMMARY

The Next Generation Weather Radar (NEXRAD) is intended to provide the basic system for the Nation's future weather radar network to serve the needs of the National Weather Service in the Department of Commerce, the Federal Aviation Administration in the Department of Transportation, the components of the Department of Defense (especially the Air Weather Service), and many external users. In order to best serve the many users and to provide a system capable of remaining abreast of the state-of-the-art well into the 21st century, NEXRAD must be a high technology system possessing some stringent design characteristics. These requirements result in fairly large cost estimates for the NEXRAD systems (a few million dollars per system). An appropriate question is whether this large planned expenditure of government funds is justified on the basis of economic benefits to be returned to the Nation during the life cycle of the NEXRAD network.

A technical requirements and economic benefits study was initiated to demonstrate how the precipitation estimation capability of the Next Generation Weather Radar (NEXRAD) would benefit the Nation, and how these potential benefits would be impacted if the technical characteristics, as currently planned for the NEXRAD systems, were relaxed to save some capital equipment costs. Although there are many general areas of economic benefit, including those related to aviation and general weather forecasting and severe storm and hurricane warnings, only those benefits derived from improved precipitation estimates for input to real-time hydrologic forecast procedures are addressed in this study.

The process of quantitative hydrologic forecasting consists of acquiring information about the states of the hydrologic cycle, assembling and quality controlling this information, and putting the information into models and procedures to predict the future states of a hydrologic system or subsystem (for example, the timing and extent of flooding). Often, the single most important hydrometeorological input to a streamflow prediction model is precipitation. And the precipitation estimates must be accurate, or the errors in the estimates will be magnified in the runoff and streamflow forecasts.

It has been recognized for over three decades, based on theoretical and experimental studies, that weather radar signals can be used for estimation of precipitation intensity. However, experience through the years has shown that obtaining accurate real-time estimates of precipitation from weather radar signals is a complex process and can be achieved only if the following major system requirements are met: 1) high quality signals are collected by a modern (solid-state) weather radar which meets a clearly defined set of stringent technical specifications (Table 2); 2) these signals are conditioned and preprocessed properly; 3) substantial computer processing of the preprocessed signals is carried out; 4) automated rain-gage data are incorporated into the processing; and 5) the characteristics of the total system are designed in an integrated fashion so that the data acquisition and processing can occur virtually, if not completely, automatically. Considerable progress towards meeting these requirements has been made on an experimental basis in the United States over the past 15 years. However, no system has yet been assembled which can operationally meet all of the above requirements. It is now possible to design, build, and implement such a system, based on: 1) the experience of the National Weather Service with its Digitized Radar Experiments begun in the early 70's; 2) the Joint Doppler Operational Experiments conducted by NOAA, the Air Weather Service, the Federal Aviation Administration, and the National Center for Atmospheric Research in the late 70's; 3) the expertise of private industry; and 4) the experience of other countries (especially Japan and Great Britain). The NEXRAD design is a culmination of these experiences. It reflects systems integration concepts that, to the authors' knowledge, are not currently available on the market from any vendor in this or any other country.

Individual technical specifications falling within the five major system requirement areas are examined to determine whether certain NEXRAD technical requirements might be relaxed without encountering serious degradation in precipitation estimation accuracy. It was decided that three specific technical characteristics might be candidates for relaxation: the beamwidth, the dynamic range and receiver sensitivity, and the operational reliability. It is estimated that 1) widening the beamwidth from 1.0° to 1.5°, 2) decreasing the dynamic range, with an accompanying loss in receiver sensitivity, from 93 dB to 80 dB, and 3) lowering the operational reliability from 98.9 to 96 percent, would result over a 20-year NEXRAD life cycle in a significant loss in economic benefits. Conservative estimates of the loss are as follows: $1.6B loss from the beamwidth broadening, $0.51B loss from the reduction in dynamic range, and $0.75B loss from the decrease in reliability. In all three cases the estimated loss in benefits far exceeds the capital costs of implementing the more stringent requirements.

Other individual NEXRAD technical characteristics relevant to obtaining accurate precipitation estimates are examined for possible relaxation. It is concluded that significant relaxation of any of the other technical specifications would produce a serious degradation in the accuracy of the precipitation estimates. This is not to say that relaxation of certain NEXRAD technical requirements would render the precipitation estimates useless. However, there would be a rapid growth in precipitation errors leading to significant losses in economic benefits, and soon a point would be reached where the NEXRAD precipitation estimation capability would be degraded so severely that automatic acquisition and processing becomes infeasible.

The two primary areas of economic benefits considered in the study are 1) flood damage reduction and 2) improved water management information resulting in increased efficiency of water utilization.

In order to estimate the economic benefits from flood damage reductions, a benefit model is used which relates: 1) NEXRAD system accuracy to the accuracy attainable with an equivalent density of rain gages; 2) effects of variation in basin response time to basin size; 3) reduction in errors in mean areal precipitation estimates to increasing basin size and integration time; 4) damage reduction to forecast lead time; 5) streamflow information usefulness to basin size; 6) annual flood damages to historical and future trends; and 7) distribution of damages and benefits to distribution of basin sizes in the U.S. The benefit model is used to calculate the increase in system improvements and accompanying economic benefits resulting from the use of NEXRAD radars, supported by a small number of automated rain gages, over the benefits provided by an operational network of rain gages. It is estimated that the current annual benefits and those projected over a 20-year life cycle of NEXRAD resulting from reductions in flood damages will be $245M and $8.6B, respectively.

In addition to flood damage reduction, many water management applications exist for which improved precipitation estimates from NEXRAD will produce substantial economic benefits. The current annual benefits potentially derivable from the use of improved precipitation estimates from NEXRAD as input to water management decision-making are estimated to be $485M. The total benefits projected over a 20-year NEXRAD life cycle are expected to be $17.1B. One of the primary benefits from improved water management information will be improved efficiency of reservoir operations, which will affect many of the application areas considered in this analysis, including: deferred construction of water resource facilities, agriculture, domestic water supply, and hydropower.

In deriving the benefit estimates for reduced flood losses and improved water management applications, certain assumptions had to be made which had a direct impact on the benefit estimates. The conservative approach generally was taken. As a result, the estimated benefits are probably conservative as well.

In conclusion, this study has shown that large economic benefits will be realized from a NEXRAD network with full precipitation estimation capability. The total benefits for improved flood forecasting and water management information are estimated to be $729M annually (based on current year dollars) and are projected to be $25.7B over a 20-year NEXRAD life cycle. Strong evidence is presented that the NEXRAD technical requirements as currently planned must be met in order to realize these substantial benefits. Any relaxation of the technical requirements will result in a loss in benefits which exceeds the cost of implementation of the more stringent technical requirements. A wealth of experience in this country and abroad has demonstrated that a sound, integrated system design is required if quantitative precipitation estimates suitable for real-time hydrologic forecasting are to be obtained from weather radar measurements. Any weak link in the system will negate the feasibility of applying this weather radar technology. Loss of such an opportunity would translate to a very large loss in economic benefits to the Nation.

NEXRAD Technical Requirements for Precipitation Estimation and Accompanying Economic Benefits

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1. STATEMENT OF PROBLEM AND SCOPE

The Next Generation Weather Radar (NEXRAD) is intended to provide the basic system for the Nation's future weather radar network to serve the needs of the National Weather Service in the Department of Commerce, the Federal Aviation Administration in the Department of Transportation, the components of the Department of Defense (especially the Air Weather Service), and many external users. In order to best serve the many users and to provide a system capable of remaining abreast of the state-of-the-art well into the 21st century, NEXRAD must be a high technology system possessing some stringent design characteristics. These requirements necessitate fairly large cost estimates for the NEXRAD systems (a few million dollars per system). An appropriate question is whether this large planned expenditure of government funds is justified on the basis of economic benefits to be returned to the Nation during the life cycle of the NEXRAD network.

There are several general areas of economic benefit which will be realized from NEXRAD. These include benefits related to aviation weather forecasting, general weather forecasts affecting many sections of the Nation's economy, severe storm and hurricane warnings, and precipitation estimation. This last area is the one considered in this report.

Accurate precipitation estimates are important for many applications in the fields of meteorology, hydrology, agriculture, and land/urban planning and management. This document will examine the benefits available from improved precipitation inputs to hydrologic forecast models. Tangible benefits will be demonstrated from the following: flood damage reductions; improved water control operations to increase water yields available for domestic water supply, irrigation, environmental quality, and industry; increased generation of hydroelectric power; more efficient use of navigable waterways; and more successful flood control through the use of regulated reservoirs. Non-tangible benefits, though apparent, are difficult to evaluate in terms of dollars. These benefits include greater public credibility resulting in lower resistance to the implementation of flood damage reduction measures; improved data for resolving legal conflicts; fewer conflicts arising because of over-allocation of existing water resources; and finally a greater degree of satisfaction on the part of the taxpayers, attributable to improved services.

Obtaining accurate estimates of precipitation is one of the most difficult of all environmental parameter estimation problems because of the large variability in precipitation that occurs over very short distances and short time intervals. Accurate estimates over small- to medium-sized watersheds generally cannot be obtained in real-time from rain gages alone except in networks instrumented densely with automated rain gages. Such dense gage instrumentation would be prohibitively costly to install and maintain on a nationwide basis. It has been generally accepted by many researchers and practitioners alike that the best approach to precipitation estimation on an areal basis is through the use of quantitative weather radars combined with a limited number of rain gages for "ground-truth calibrations" (Wilson, 1971; Gorrie and Kouwen, 1978; Wilson and Brandes, 1979; and Collier, 1984).

Although, as identified above, there are several areas where improved precipitation estimates from NEXRAD potentially will provide large economic benefits, only the two largest ones in the hydrologic area are considered in this analysis. These are: 1) flood loss reductions and 2) savings from improved water management information. There will be other benefits to hydrologic applications from improved precipitation estimates which are less direct and more difficult to quantify. For instance, a potentially very large benefit may result from the feedback coming from improved capabilities of meteorological prediction of precipitation and temperature on the mesoscale, which in turn would improve hydrologic prediction skill and lead time, especially on small- and intermediate-sized basins. However, the analysis presented here is confined to the two benefit areas above and considers only the benefits from accurate observations of precipitation that has already fallen and not the potential benefits that may be realized from improved predictions of future precipitation.

The analysis will consider the improvements expected in hydrologic predictions if a NEXRAD network, complemented with approximately 30 automated rain gages per NEXRAD umbrella, is used instead of a rain-gage-only network similar to the one currently used for operational forecasting. The characteristics of the NEXRAD system required to achieve these benefits are described, and evidence is presented that use of a system with lesser characteristics will result in a loss of benefits (perhaps even a total loss) that would far exceed the capital costs for implementation of the desired characteristics. Section 2 identifies and discusses five major system requirement areas necessary to obtain accurate real-time estimates of precipitation useful for real-time hydrologic forecasting from weather radar signals. In Section 3 this information is used to evaluate whether or not a relaxation of any technical specifications might be possible. Section 3 also examines the impact on benefits that any possible relaxations of specifications would have, in order to evaluate their cost effectiveness. Section 4 presents a comprehensive analysis of the flood damage reduction and water management benefits which will be derived from a network of fully equipped NEXRAD systems that include the Precipitation Processing Subsystem (PPS).

2. CHARACTERISTICS OF NEXRAD REQUIRED TO DERIVE ECONOMIC BENEFITS

2.1 Background

Since the late 1940's and early 1950's the potential for using weather radar signals for estimation of precipitation intensity has been recognized and many theoretical and experimental studies have been conducted since that time in an attempt to produce techniques that could be used operationally. Although use has been made of radar precipitation estimates through the years in qualitative and semi-quantitative ways, over 30 years of development and experimental activities still have not produced operational systems in the United States capable of providing consistently reliable quantitative precipitation estimates. There are several reasons for this, but the fundamental one has been the lack of an integrated systems approach to the problem. The operational feasibility has been established by the Japanese and British, who are ahead of the United States in many aspects of the use of radar precipitation estimates for water resources management (CWPU, 1977; Ishizawka et al., 1979; Japan Radio Co., 1980; and Collier, 1980, 1984).

The process of quantitative hydrologic forecasting consists of acquiring information about the states of the hydrologic cycle, assembling and quality controlling this information, and putting the information into models and procedures to predict the future states of a hydrologic system or subsystem. Such predictions, for example, might include the timing and extent of flooding. Often, the single most important hydrometeorological input to a streamflow prediction model is precipitation. And the precipitation estimates must be accurate, or the errors in the estimates will be magnified in the runoff and streamflow forecasts. Figure 1 helps illustrate the importance of accurate precipitation estimates in the derivation of runoff forecasts. This figure illustrates that the transformation of precipitation to runoff is nonlinear and can have the effect of magnifying errors. The total precipitation error for a single storm event and precipitation amount, expressed as percent error, is compared to the corresponding total percent runoff error.

Obtaining accurate real-time estimates of precipitation from weather radar signals is a complex process and can be achieved only if the following major system requirements are met: 1) high quality signals are collected by a modern weather radar which meets a clearly defined set of stringent technical specifications (Section 2.2.1); 2) these signals are conditioned and preprocessed properly (Section 2.2.2); 3) substantial computer processing of the preprocessed signals is carried out (Section 2.2.3); 4) automated rain-gage data are incorporated into the processing (Section 2.2.4); and 5) the total system is properly integrated so that data acquisition and processing can be automated to the maximum extent possible (Section 2.2.5). Considerable progress towards meeting these requirements has been made on an experimental basis in the United States over the past 15 years. However, no system has yet been assembled which can operationally meet all of the above requirements. It is now possible to design, build, and implement such a system, based on: 1) the experience of the National Weather Service with its Digitized Radar Experiments begun in the early 70's (Saffle, 1976; Tetzloff, 1976); 2) the Joint Doppler Operational Experiments conducted by NOAA, the Air Weather Service, the Federal Aviation Administration, and the National Center for Atmospheric Research in the late 70's (Burgess, 1978); 3) the expertise of private industry; and 4) the experience of other countries. The NEXRAD design is a culmination of these experiences. It reflects systems integration concepts that, to the authors' knowledge, are not currently available on the market from any vendor in this or any other country. NEXRAD development exemplifies a cooperative effort between the Federal government and private industry, through the A-109 procurement process, which should lead to the production of a weather radar system that will not only meet the needs of our Nation well into the 21st century but will probably be able to effectively compete for sales in other countries. This potential success does, however, depend on the implementation of a system that incorporates an accurate precipitation estimation capability.

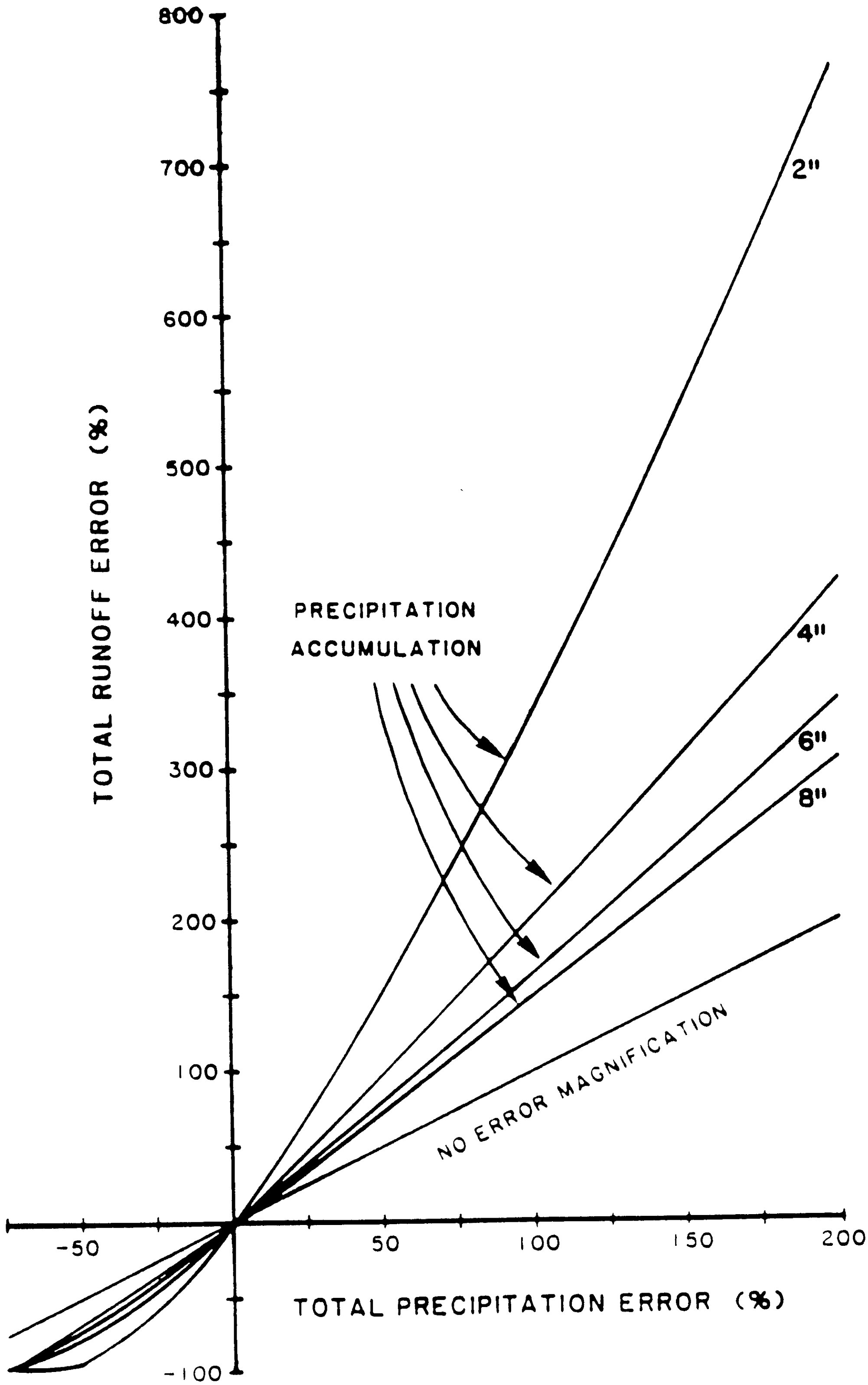


Figure 1. Example illustration of magnification of precipitation error in runoff estimates for a single storm event, using a rainfall-runoff prediction model which is assumed to have no error (Hudlow et al., 1983).

2.2 Specific Technical Characteristics Required of NEXRAD

As described above, high-quality uninterrupted precipitation estimates must be produced in real-time by NEXRAD if they are to be used for quantitative hydrologic forecasting. The five major system requirement areas, identified in Section 2.1, necessary to achieve this level of quality, reliability, and timeliness are discussed below.

2.2.1 High quality raw radar signals

The principal radar characteristics which affect the quality of the raw radar signal for the purposes of precipitation estimation include wavelength, beamwidth and sidelobe patterns, receiver sensitivity and dynamic range, electronic calibration stability, acquisition or scanning strategy/capability, and high operational reliability. Because of the significance of these characteristics, a separate subsection is devoted to each to show how they relate to the generation of accurate precipitation estimates useful for quantitative hydrologic applications.

2.2.1.1 <u>Wavelength</u> - The choice of wavelength is critical for precipitation estimation, since the attenuation of the transmitted and received signals by intervening precipitation and atmospheric constituents (oxygen and water vapor) can totally obliterate the signal (target) in the X-band (λ = 3 cm) and introduce large errors in the C-band (λ = 5 cm) [Skolnik, 1970; Weible and Sirmans, 1976; Allen et al., 1981]. For accurate precipitation estimation, it is not acceptable to just "see" part or all of the precipitation echo, but an accurate estimate of its intensity over the total area must be obtained. Weible and Sirmans (1976) have demonstrated that serious attenuation problems occur during radar observation of regions of heavy rainfall at a wavelength of 5 cm. They found that rainfall depths, computed with simulated rainfall rate attenuation at the radar wavelength of 5 cm, underestimated the unattenuated depths, obtained with a 10 cm radar during an actual thunderstorm, by about 120 mm over an area of 90 km^2. Procedures to correct for attenuation, even in light to moderate precipitation, are not feasible for X-band and are unreliable and introduce significant uncertainties when applied in real-time with C-band radars. Because of the attenuation problems at shorter wavelengths, Battan (1973) and others recommend that S-band radars (λ = 10 cm) should be used whenever possible for quantitative rainfall measurement.

An error analysis by Hitschfeld and Borden (1954) indicated that applying attenuation corrections to C-band precipitation estimates can produce large errors unless the calibration of the radar and the precipitation structure (partial beam filling, drop size distribution) are very accurately known. Since these quantities are not precisely known, attempting to correct for attenuation will, in many cases, result in errors even larger than those that would occur if no correction had been applied. A case study made by Geotis (1975) showed that C-band attenuation estimates, obtained by intercomparison with overlapping S-band measurements, may be as large as 15 dB (3000 percent attenuation of signal) under very heavy intervening rainfall situations. Geotis concluded that attenuation could not be easily compensated for in real-time and that correction errors can grow excessively large, especially in heavy rainfall.

Table 1 gives estimates of the number of hours during which maximum attenuation amounts from intervening rainfall were encountered with the C-band radar aboard the ship OCEANOGRAPHER during the GARP Atlantic Tropical Experiment (GATE) (Hudlow et al., 1979). These estimates (which are probably conservative) were determined by very careful postanalyses and show that during 275 out of 822 hours (33 percent), more than 1 dBR attenuation was present. (dBR = 10 $\log_{10}R$, where R is the rainfall rate in mm/hr.) One dBR attenuation would be approximately equivalent to a 25 percent error in rainfall rate and 3 dBR would correspond to approximately 100 percent error. A compounding of the attenuation problem is encountered when rain falls on the radar's radome, forming a water coating which further attenuates the signals. This problem is more severe at shorter wavelengths (X- and C-band) than it is for S-band radars. Figure 2 illustrates the effects of wet-radome attenuation when a rain shower passed over the OCEANOGRAPHER radar during GATE. The total volumetric water being observed by the radar dropped by over 300 percent. And the mean rainfall rate which produced this significant drop, as measured by the shipboard rain gage, was 20 mm/hr (< 1" per hr), an intensity which is frequently exceeded.

Table 1. Estimates of maximum attenuation encountered from intervening rainfall during 822 hours of observations collected with a C-band radar during GATE.

	Number of hours	Maximum intervening rain attenuation (dBR)
	547	0 - 1
	165	1 - 2
	81	2 - 3
	23	3 - 4
	6	4 - 5
Total hours	822	

Both intervening rainfall and wet-radome attenuation corrections were applied to the rainfall estimates derived from the C-band measurements made during GATE (Patterson et al., 1979). However, these corrections were applied in a postanalysis (non real-time) mode. During the course of these postanalyses, it was found that an overestimate of only 1.3 dBR in the wet-radome attenuation corrections resulted in physically unrealistic corrections for intervening rainfall attenuation. This led Patterson et al. (1979) to report that the attenuation correction procedure for intervening rainfall, which uses a cumulative logarithmic function, will give unstable solutions leading to unrealistically high correction values if: 1) the initial data fields contain small positive biases or 2) the coefficients for the assumed drop-size distribution are in error.

The above studies document that unacceptably large attenuation values are encountered in the C-band (and even larger ones in the X-band). They also strongly suggest that real-time correction procedures cannot accurately account for signal losses from rainfall attenuation; in fact, attempts to correct can lead to errors larger than those that would occur if no corrections are applied.

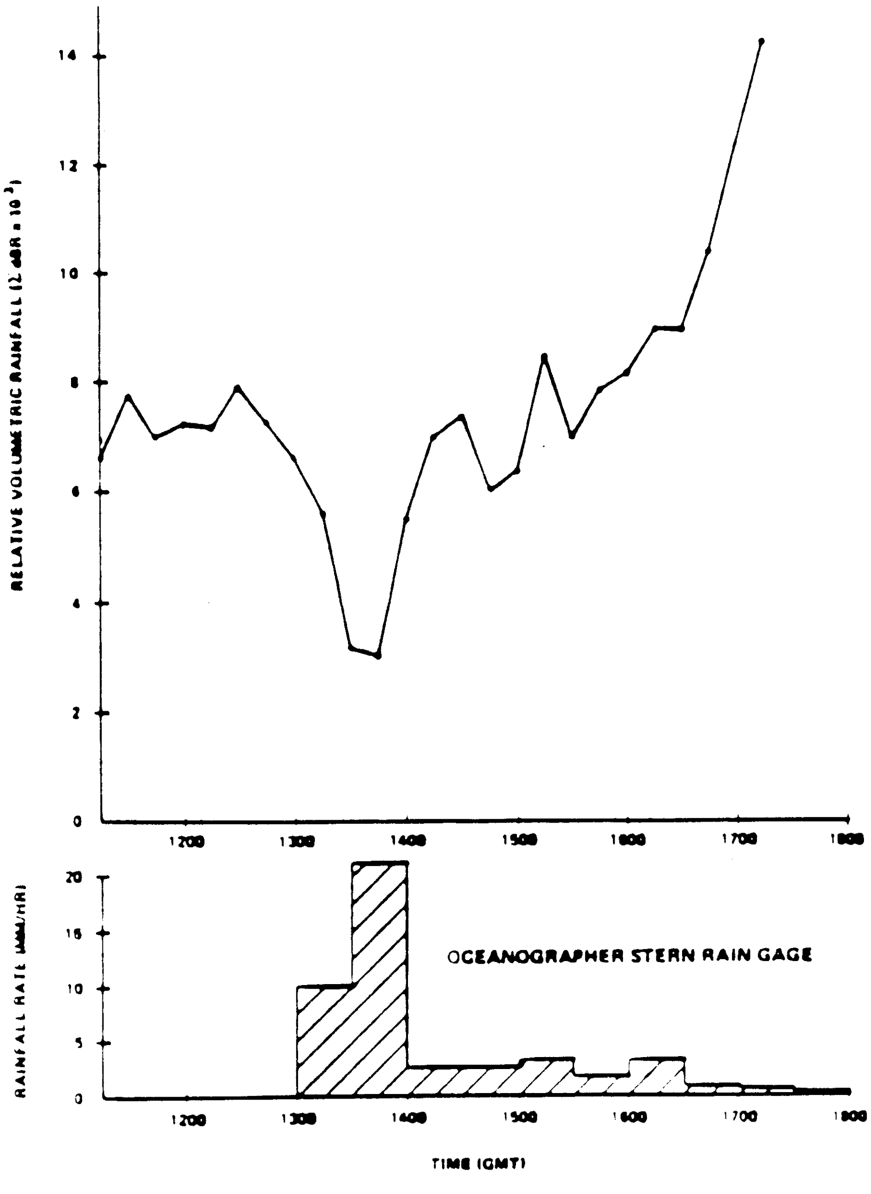


Figure 2. Illustration of the effects of wet-radome attenuation during rain for a C-band radar used during GATE. Upper panel is a plot of the total volumetric water (dBR units) estimated from radar and the lower panel is a corresponding plot of rainfall rate (mm/hr) at the radar site (Hudlow et al., 1979).

Such magnitudes of attenuation errors cannot be tolerated if sufficiently accurate estimates of rainfall are to be obtained for quantitative streamflow forecasting. (Again, refer to the example of error magnification, which even further compounds the problems, illustrated in Figure 1.) The magnitudes of attenuation observed during GATE would be typical for any place in the United States at any time when moderate to heavy rainfall is experienced. There is virtually no place in the United States that does not experience such rainfall sometime during the year.

CONCLUSION — Only S-band radars ($\lambda \approx 10$ cm) can provide the accuracy required for reliable quantitative precipitation estimation because significant attenuation problems are not encountered in the S-band, while intolerable errors accompany C-band measurements and data are totally obliterated in the X-band. Furthermore, corrections for these errors in real-time are unreliable.

2.2.1.2 - Beamwidth and sidelobe patterns — The effect of beamwidth and sidelobe patterns on the accuracy of precipitation estimation can be substantial. Both can have large impacts on ground clutter and anomalous propagation (AP) signals which must be totally removed during the signal preprocessing and software processing or they will seriously contaminate the rainfall estimates. The wider the beamwidth and the stronger the side lobes, the stronger and more widespread these clutter signals will be, and the more difficult it will be to remove them without serious degradation or total loss of rainfall data in the affected areas.

The beamwidth also will critically impact the range performance of the radar, i.e., the drop-off in accuracy of rainfall measurement as a function of range from the radar. The range degradation observed with the 2° beamwidth WSR-57 radar, for example, causes reflectivity to be underestimated by a factor of 1.6 at 180 km and a factor of 4.0 at 280 km for Oklahoma thunderstorms [Baxter, 1966]. This drop-off in accuracy is significant, since the precipitation estimates by the NEXRAD system are to be made out to a range of 230 km. If we were to reduce this range, additional radars would be required to give the same coverage. This drop-off occurs because the beam ascends above the surface of the earth and spreads as the distance away from the radar increases; thus, the beam reaches a point where it is no longer filled by the shallower echoes and eventually overshoots even the higher portions of the storm.

Figure 3 provides a relative comparison in mean range performance for 1°, 1.5°, and 2° beamwidth radars for convective rainfall. Figure 3 also illustrates the relative increase in deterioration in range performance for a 2° beamwidth radar with change in precipitation type from convective rainfall to stratiform rainfall to snowfall. Several effects are apparent as a function of beamwidth. First, the range where degradation begins in convective rainfall increases as the beamwidth decreases ($\approx$ 100 km for 2°, $\approx$ 120 km for 1.5°, and $\approx$ 150 km for 1° for convective rain). Second, the fall-off doesn't drop below 25 percent until about 200 km for the 1° beam. Third, because of the lower intensities and shallower storm depths, range degradation will be significantly greater in stratiform rainfall than in convective rainfall. Fourth, because of the large difference in dielectric constant between snowflakes and raindrops, the lower snowfall rates, and the lower altitudes to which snow showers extend, the range performance for snow is much worse than for rain. Accordingly, measurement of snow will not be possible at extended ranges without a narrow beamwidth (1° or less).

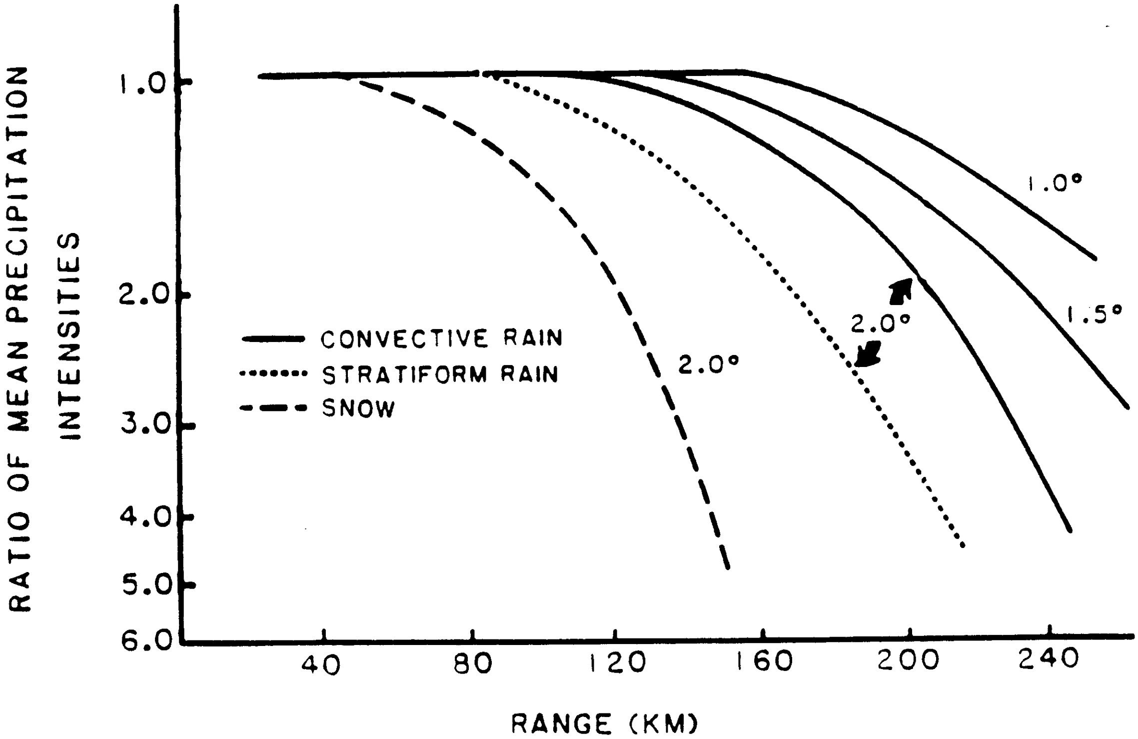


Figure 3. Range performance curves for 3 beamwidths illustrating relative drop-off in measurement of mean precipitation intensity expressed as a ratio of the precipitation intensity at further range to the intensity at close range before drop-off begins. The 2° curve for rain is based on results from Wilson (1971). Other curves are based on the authors' experiences with radar data.

Empirical corrections can be applied to correct for range fall-off in the mean. However, errors accompanying the corrections for individual storms will increase as the magnitude of the mean correction increases. This fact limits the maximum range for which corrections realistically can be applied since the variance about the mean curves shown in Figure 3 can be quite large and will increase with range.

Another important impact of beamwidth on precipitation estimation is its direct relationship to horizontal resolution. The final precipitation products from NEXRAD will be displayed or input into hydrologic models in the form of grid arrays. In order to resolve the detail of rainfall structure that can cause flash floods, the basic grid size must not exceed 2 km x 2 km. To achieve reasonable estimates of rainfall at this resolution out to the maximum range of rainfall estimation (230 km), the horizontal width of the beam at mid-range (i.e., 115 km) must be approximately equal to the 2-km required resolution. A 1° beamwidth at 115 km gives a width of 2 km, 1.5° gives 3 km, and 2° gives 4 km. Clearly, a beamwidth greater than 1° will not fully satisfy the precipitation resolution requirements, especially for flash-flood applications.

<u>CONCLUSION</u> — A 1° beamwidth is required to fully meet the precipitation estimation requirements. A 1.5° beamwidth would result in substantial loss of accuracy at ranges beyond 150 km from the radar for rain and would severely limit the capability of the system to quantitatively estimate snowfall rates. A 2° beamwidth would make it impossible to estimate precipitation to the required accuracy out to the ranges necessary for complete coverage in the far range regions between radars.

2.2.1.3 - <u>Receiver sensitivity and dynamic range</u> -- The dynamic range of precipitation signals is more than 80 dB, including signals from dry snow at the low end and from heavy rain and hail at the upper end. The effects of range performance as illustrated in the foregoing subsection will be even more accentuated if the radar receiver is not sufficiently sensitive. One way to look at this is as follows. NEXRAD should be designed with the sensitivity to give clear air returns at close ranges; this sensitivity will also provide the capability to quantitatively measure snowfall at middle and, under certain conditions, even at farther ranges. This, in turn, will assure the detection of light rainfall at the farther ranges, which is important for input to soil moisture accounting models.

A significant factor further supporting the 93 dB dynamic range as specified in the NTR [NEXRAD Technical Requirements (NEXRAD JSPO, 1984)] is that the superposition of ground clutter signals on the precipitation signals in certain areas will effectively reduce the observable dynamic range of precipitation signals. Although the area of maximum precipitation in a convective storm generally will cover only a small portion of the total storm area, the precipitation in this area may account for the majority of the total storm rain water (see Figure 4). Therefore, it is extremely important that accurate measurements be obtained in these heavy cores of precipitation.

<u>CONCLUSION</u> -- The dynamic range and the receiver sensitivity specified in the NTR (NEXRAD JSPO, 1984) are required if the precipitation signals are to be effectively measured over the necessary range of intensities out to the required 230 km from the radar.

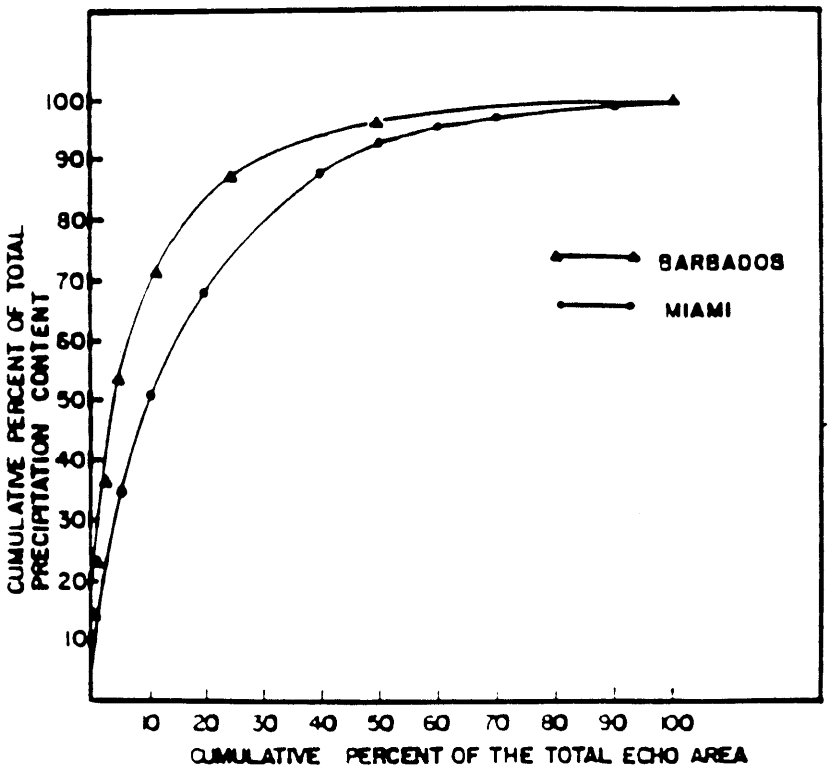


Figure 4. Mean relative cumulative distributions of precipitation content for percentages of the total echo area for radar echoes observed in the Barbados and Miami vicinities (Hudlow & Scherer, 1975).

2.2.1.4 - Electronic calibration stability -- In order to obtain accurate estimates of reflectivity from radar measurements, several parameters entering the solution of the radar equation must be calibrated with a high degree of accuracy and precision. These include, for example, the transmitted power, the antenna gain, and the radar receiver response function.

Reflectivity estimates with an accuracy of 1 dB or better are essential to meeting the final necessary accuracies in the precipitation estimates, since additional errors will be encountered in the transformation of reflectivities to precipitation rate estimates. If the errors in reflectivity data input into the NEXRAD PPS are too large, the cumulative error in the precipitation accumulations will exceed allowable tolerances even after adjustments are made with data from automated rain gages.

CONCLUSION -- Even with the modern solid-state electronics planned for NEXRAD, there will be a need for automatic monitoring of equipment status and calibration functions in order to achieve the required accuracy of 1 dB in the reflectivity measurements.

2.2.1.5 - Acquisition or scanning strategy/capability -- NEXRAD must provide the capability to automatically collect volume scans of data every 5 minutes, including sequential, contiguous scans for at least the lowest four antenna tilt settings covering the volume from the base tilt up to at least 3.5° elevation. These multiple tilt data are required for accurate precipitation estimation since they will be used in the PPS to construct a hybrid scan to minimize ground clutter and AP and to provide a map of precipitation estimates at an approximate constant altitude relative to the earth's surface. The need for these data every 5 minutes during precipitation periods can be seen from Figure 5, which illustrates the increase in errors as the sampling interval is increased. The top graph in Figure 5 shows that increasing the sampling interval from 5 to 10 minutes increases the hourly precipitation estimate error on the average by about 5 to 15 percent, depending on the averaging area.

Figures 6 and 7 provide an example of the capability of the NEXRAD PPS to use multiple tilt-scan data to reduce or eliminate ground clutter (Ahnert et al., 1983, 1984). These data are from the NCAR CP-2 radar located in Boulder, Colorado. Much of the echo west of the radar in Figure 6 is ground clutter return from the Rocky Mountains. A major mesoscale area of precipitation lies to the southeast of the radar. A comparison of the two pictures (Figures 6 and 7) illustrates the reduction in clutter achieved by using "sectorized hybrid" processing instead of base-tilt reflectivity data only. This type of processing, along with the planned 30 dBZ clutter suppression in the reflectivity channel of NEXRAD, should eliminate almost all ground clutter.

CONCLUSION -- NEXRAD must provide the capability to collect the multiple-tilt reflectivity data required to accomplish the processing every 5 minutes during precipitation as illustrated in Figure 5 or it will not be possible to obtain precipitation estimates of the required accuracy with minimum ground clutter contamination.

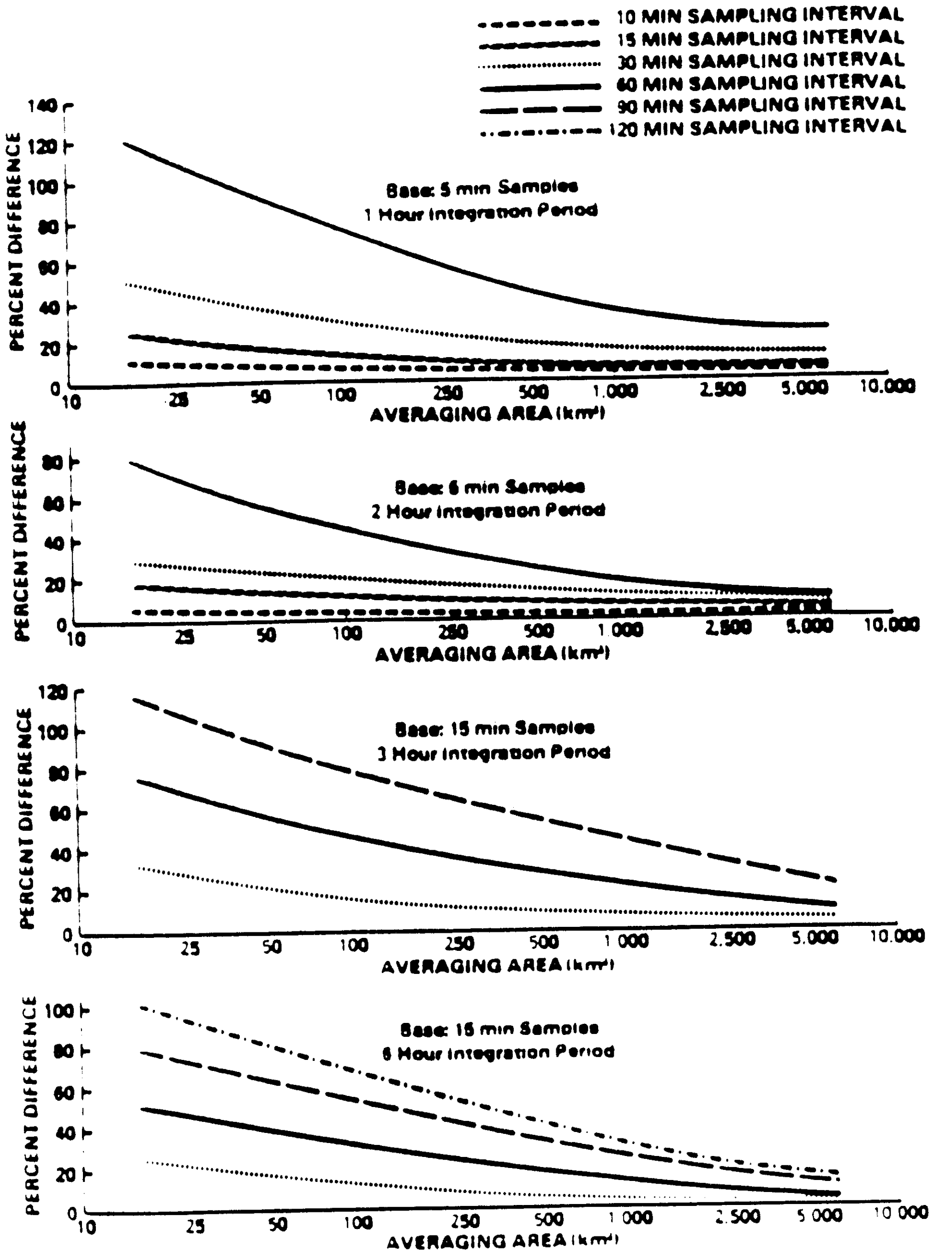


Figure 5. Upper two panels: Mean absolute percent difference between rainfall estimates using 5-min base sampling intervals and those from coarser sampling intervals for a range of spatial averaging and temporal integration scales. Lower two panels: Same as upper two, except a 15-min base sampling interval was used and longer integration periods were included (Hudlow & Arkell, 1978).

2.2.1.6 - High operational reliability -- The NEXRAD system must provide an uninterrupted stream of reflectivity data to the NEXRAD PPS in order to obtain accurate precipitation estimates. Figure 5 illustrates the errors in precipitation estimates that will be encountered for various sizes of watershed areas as the interval between observations (sampling interval) increases, due to equipment failures or other causes. These sampling errors occur because precipitation varies significantly over short time intervals.

A major factor related to the need for a high operational reliability for NEXRAD is the distribution of down times throughout the year. Experience has demonstrated that outages will occur more frequently during severe weather and heavy rainfall, which is when the need for the radar data is most critical.

CONCLUSION -- From examination of Figure 5, a NEXRAD operational reliability approaching 100 percent is required if complete losses in storm coverage are to be avoided and if the precipitation estimation errors are to be kept at a tolerable level (< 25 percent), especially for the smaller watersheds where flash-flood potential is greatest.

2.2.2 - Properly conditioned and preprocessed signals

Once the high quality raw radar signals have been collected, they must be conditioned and preprocessed before they enter the NEXRAD PPS. The primary conditioning requirements for obtaining accurate precipitation estimates involve signal processing to reduce the variance of the reflectivity estimates to 1 dB or less and to suppress ground clutter by at least 30 dB. As mentioned above, even with the sectorized hybrid processing as illustrated in Figure 7, clutter suppression at the preprocessing stage is required to eliminate most ground clutter in order to obtain precipitation estimates useful for input to automated forecast procedures. Suppression of less than 30 dBZ would result in the recovery of less than 50 percent of the area obscured by ground clutter. Increasing the clutter suppression capability beyond 40 dBZ would significantly increase cost and would impact scanning strategy and dwell time requirements. Therefore, the optimum practical ground clutter suppression is 30-40 dB. The Doppler channel data will provide valuable information for achieving the desired level of clutter suppression.

CONCLUSION -- Signal conditioning and preprocessing must reduce the variance of the reflectivity estimates to 1 dB or less and suppress ground clutter by 30-40 dB.

2.2.3 - Computer processing of the preprocessed signals

Once the preprocessing is complete, the multiple-tilt data must be passed in real time every 5 minutes to an on-site computer facility. Figure 8 illustrates the minimum components and functions required in order to generate consistently reliable quantitative precipitation estimates as required for hydrometeorological applications. This Precipitation Processing Subsystem (PPS) is a composite of the system components and functions demonstrated to be necessary during field studies and experiments (Wilson, 1971; Hudlow and Scherer, 1975; Hudlow and Arkell, 1978; Saffle, 1976; Tetzloff, 1976; Hudlow et al., 1979; Patterson et al., 1979) and during the development and testing of operational systems in other countries (CWPU, 1977; Ishizaki et al., 1979; Japan Radio, 1980; Collier, 1980, 1984). The PPS has been developed and

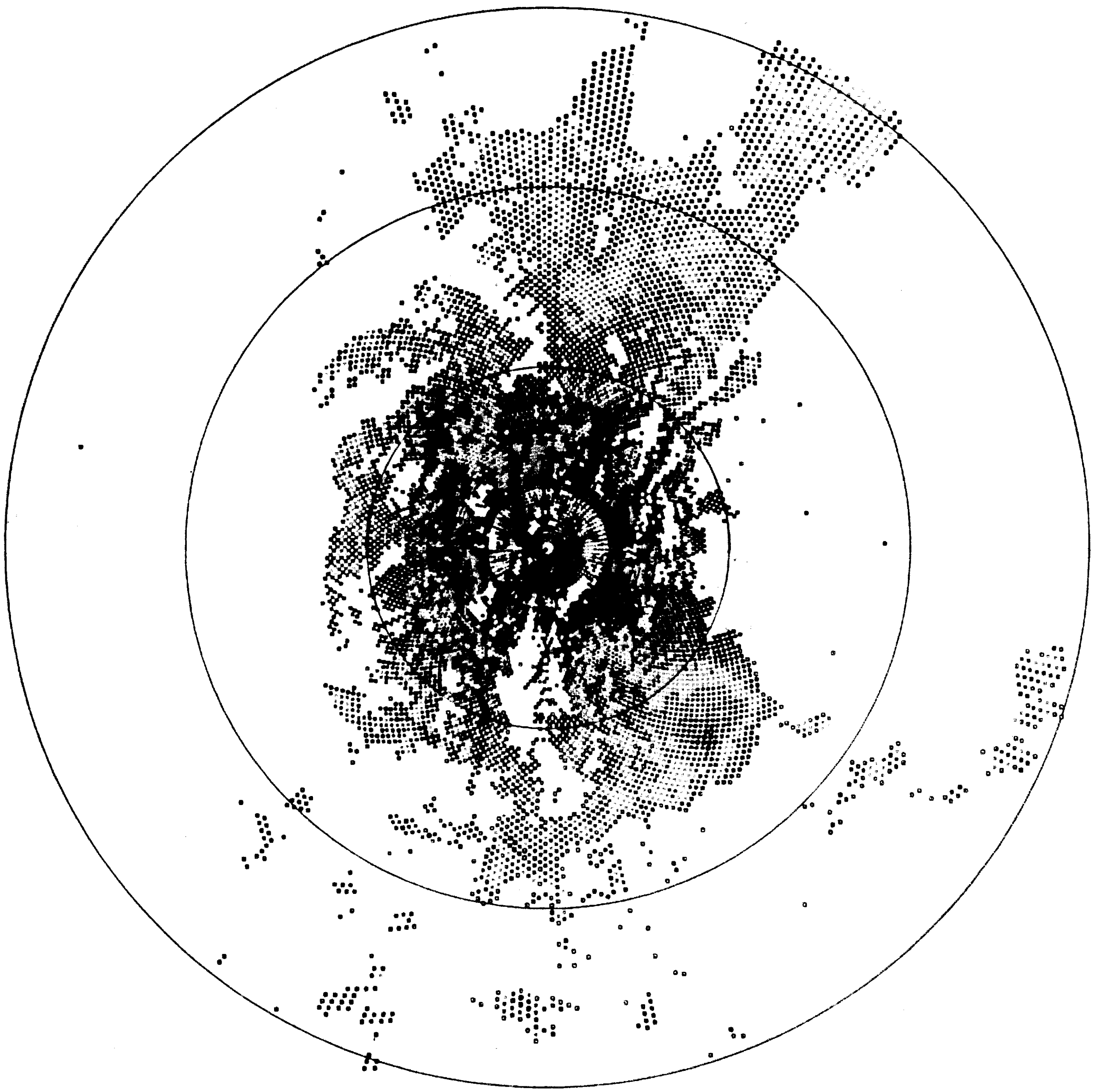
REFLECTIVITY

TIME: 21:00Z DATE: JULY 23, 1983

RANGE MARKER INTERVAL: 50 KM

COLOR	dBz	COLOR	dBz	COLOR	dBz
BLUE	0 - 10		21 - 30	RED	41 - 50
GREEN	11 - 20	MAGENTA	31 - 40	BROWN	> 51

Figure 6. Example base-tilt display (see text).

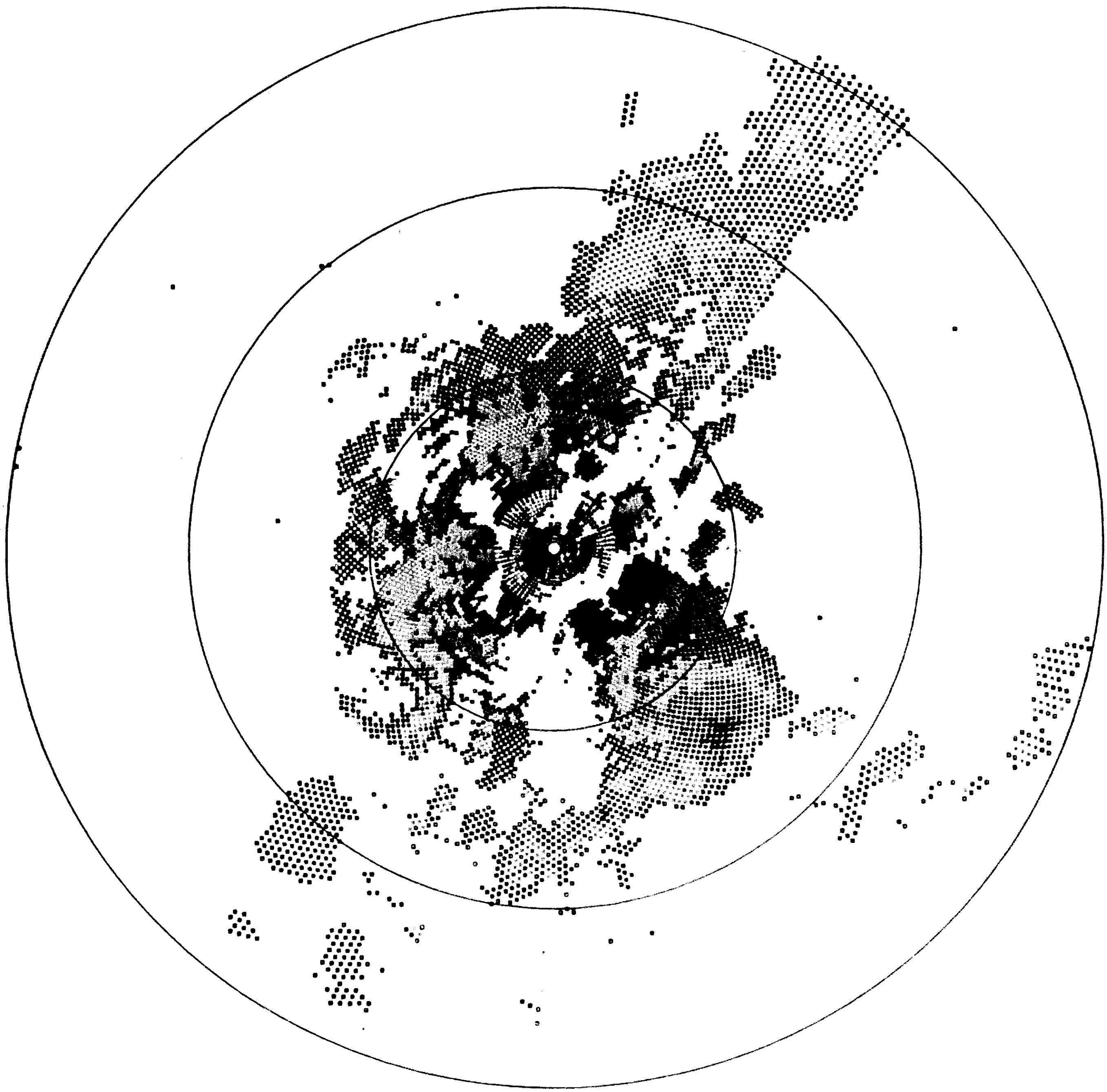


REFLECTIVITY

TIME: 21:00Z DATE: JULY 23, 1983
RANGE MARKER INTERVAL: 50 KM

COLOR	dBz	COLOR	dBz	COLOR	dBz
BLUE	0 - 10	[illegible]	21 - 30	RED	41 - 50
GREEN	11 - 20	MAGENTA	31 - 40	BROWN	> 51

Figure 7. Example sectorized hybrid display (see text).



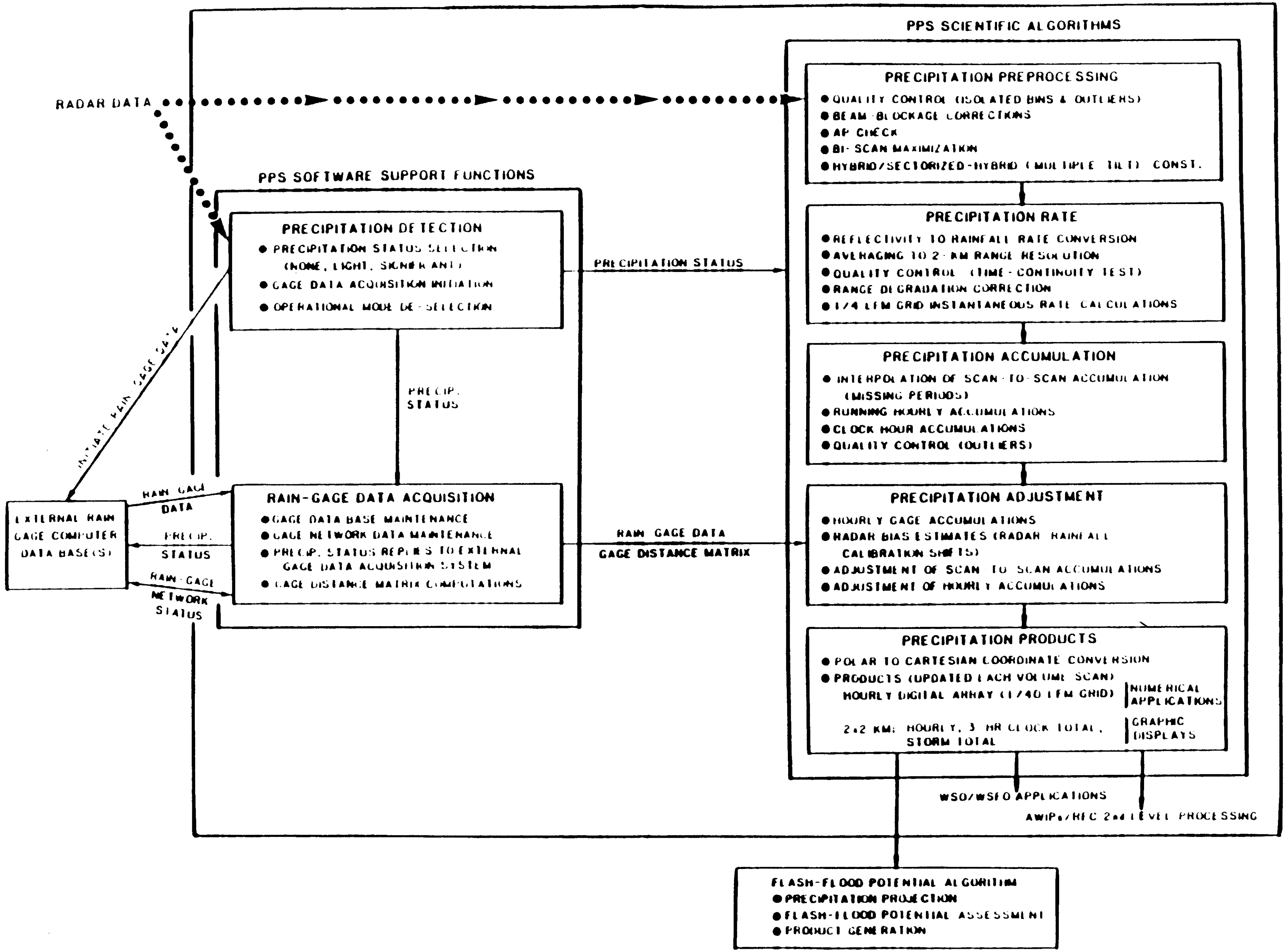


Figure 8. Schematic illustration of the functions and algorithms comprising the NEXRAD Precipitation Processing Subsystem (PPS)

tested using data from a National Center of Atmospheric Research radar which has characteristics similar to those planned for NEXRAD. One phase of the testing consisted of analyzing the effects of the various components of the PPS on the precipitation estimates. For example, the check for extreme reflectivity values (outliers) reduced the false hourly accumulations due to mountain clutter by 25 to 50 percent (averaged over various regions) and the sectorized-hybrid (multiple-tilt) construction further reduced the false accumulations by 50 to 90 percent. For further results, refer to the "Validation of the 'On-Site' Precipitation Processing System for NEXRAD" by Ahnert et al. (1984). The results of those analyses, along with the results of earlier studies, verified the need for the processing steps comprising the state-of-the-art modular system illustrated in Figure 8. This design is based on extensive research and operational experience in this country and abroad and is considered to provide an optimal framework which will allow future refinements without the necessity for major system redesign.

<u>CONCLUSION</u> — Adequate real-time computer processing capabilities, as illustrated in Figure 8, must be available at the radar site, or sufficient communication capability must be available to communicate the basic radar reflectivity data to a suitable external computer facility, if the required level of quantitative accuracy for hydrologic forecasting is to be achieved.

2.2.4 - Incorporation of automated rain-gage data into processing

Although high quality reflectivity data will be provided by NEXRAD, other sources of error in the conversion of reflectivity to rainfall rate make it essential to use data in real-time from several automated rain gages to adjust the radar derived rainfall fields to "ground truth." Thirty years of research, development, and experimentation have proven that consistently accurate radar rainfall estimates cannot be obtained without such "ground-truth" observations. Figure 8 illustrates how the rain-gage data acquisition and processing function will be incorporated as part of the PPS.

<u>CONCLUSION</u> — The inclusion of "ground truth" rain-gage data is a primary requirement for the hydrologic applications of the NEXRAD system.

2.2.5 - Integrated system design for automatic data acquisition and processing

The NEXRAD acquisition, preprocessing, processing, and output must be executed in a sequential stream whereby the results from each successive step are passed automatically in real-time to the next step. This stream must be designed to take advantage of the inherent characteristics of the radar data at each step so that maximum accuracy, quality control, and processing efficiency, and minimum data volume retention can be achieved. For example, the computations will be executed in polar coordinates (the natural radar coordinate system) up to the point that conversions are made to produce the output products. Processing should be continual in the sense that rainfall accumulations must be computed from scan-to-scan (and longer) time-period integrations. The scan-to-scan accumulations must be maintained even during clear air operations when no significant rain exists under the radar umbrella, although most of the processing steps are bypassed under this condition. The rainfall integrations will require considerable internal time accounting and synchronization for both the radar data and the automated rain-gage data used for adjustments.

The considerable experience gained through the NWS Digitized Radar Experiments (D/RADEX) beginning in the 70's has demonstrated that all components of the total hardware/software system must be integrated and functioning properly if sufficiently accurate precipitation estimates are to be obtained for input to quantitative hydrologic forecasting procedures. And, because of the voluminous amounts of data involved, the shortage of personnel, and the real-time forecast requirements, the system must provide the precipitation products virtually, if not totally, automatically.

CONCLUSION -- The design characteristics described in the above sections for the NEXRAD system, from data acquisition to processing in the PPS, must be integrated into a system capable of automatically providing precipitation products of high quality.

3. IMPACT OF REDUCING NEXRAD TECHNICAL REQUIREMENTS

Section 2 presented the NEXRAD technical requirements for obtaining accurate precipitation estimates from the NEXRAD system. An appropriate issue is whether some of these requirements might be relaxed and still: 1) obtain quantitative precipitation estimates acceptable for real-time hydrologic forecasting applications and 2) realize no major losses in economic benefits.

Table 2 summarizes the major requirement areas and associated technical characteristics, as presented in Section 2, that are critical to the accurate estimation of precipitation for real-time hydrologic forecasting. Table 2 also presents the results of an examination of these requirements to determine whether any of them might be relaxed. This examination identified only three technical requirements which might possibly be relaxed and still allow the derivation of estimates of precipitation that would be sufficiently accurate to be acceptable for use in real-time hydrologic forecasting applications. These are the requirements on: beamwidth (with some possible increase in side lobe intensities), dynamic-range/sensitivity, and operational reliability. The associated question of loss in economic benefits which would be incurred over a 20-year life cycle for NEXRAD as a result of these changes is also examined.

3.1 Impact of Increasing the Beamwidth from 1° to 1.5°

The curves for convective rainfall presented in Figure 3 were used to answer the question of how much increase in the estimates of mean error of rainfall would be incurred by widening the beamwidth from 1° to 1.5°. The approach was simply to average the increase in error over discrete annuli making up the total area of the circular radar umbrella. Table 3 summarizes the results of these computations.

The increase in error of mean precipitation estimation was then translated through the benefit models contained in Section 4 to arrive at an estimate of the loss in benefits that would be incurred. In the case of the benefit model for flood loss reduction, the Forecast Lead Time (FLT) penalty (which causes an adjustment in the benefit associated with potential FLT) was increased through an adjustment of the coefficient of variation (CV) of the mean basin precipitation error. When this calculation was performed, the percent loss in benefits was found to be nearly twice the percent increase in the error of precipitation. To avoid letting model approximations bias the

Table 2. Summary of major requirement areas and technical characteristics of NEXRAD needed to meet precipitation estimation accuracies for real-time hydrologic forecasting, including examination of possible relaxation of these requirements.

MAJOR REQUIREMENT AREA	SUBAREA TECHNICAL CHARACTERISTICS	RELAXATION OF REQUIREMENT POSSIBLE: NO	RELAXATION OF REQUIREMENT POSSIBLE: YES	MINIMAL REQUIREMENT WITH RELAXATION	EST. IMPACT ON: PRECIPITATION-ERROR[1] (ECONOMIC BENEFITS)[2]	COMMENTS
High quality raw radar signals	Wavelength = 10 cm	X				Attenuation is prohibitively large at shorter wavelengths and real-time corrections to remove biases are not reliable.
	Beamwidth = 1° with NTR specified sidelobe characteristics		X	Beamwidth $\leq$ 1.5°	6.2% (-\$1.6B)	Degradation of beamwidth from 1° to 1.5° will result in substantial loss in accuracy for rain beyond 150 km and an even more serious degradation of snowfall measurements.
	Dynamic range > 93 dB with sensitivity as specified in NTR		X	Dynamic range $\geq$ 80 dB	2.0% (-\$0.51B)	Reduction in dynamic-range/sensitivity will cause loss of accurate measurement of some heavy rain cores on high end and will reduce the effective range of dry snow measurement on low end.
	Electronic calibration stability including automatic monitoring/calibration	X				Calibration stability cannot be held to within 1 dB without this automatic provision.
	Multiple-tilt automatic scanning strategy with 5-min update	X				Clutter and AP elimination, automatic quality control, and temporal sampling requirements preclude relaxing this requirement.
	High operational reliability (NTR specifies 98.9%)		X	Operational reliability $\geq$ 96%	(-\$0.75B)	Lowering of operational reliability will cause some complete losses in storm coverage and an increase in estimation error during other periods when interval between samples is too large.

[1] Estimated mean percent increase in error.
[2] Estimated loss in benefits over a 20-year period.

Table 2 (continued)

MAJOR REQUIREMENT AREA	SUBAREA TECHNICAL CHARACTERISTICS	RELAXATION OF REQUIREMENT POSSIBLE: NO	RELAXATION OF REQUIREMENT POSSIBLE: YES	MINIMAL REQUIREMENT WITH RELAXATION	EST. IMPACT ON: PRECIPITATION-ERROR[1] (ECONOMIC BENEFITS)[2]	COMMENTS
Properly conditioned and preprocessed signals	Signal processing to reduce variance of reflectivity estimate to ≤ 1 dBZ	X				Larger reflectivity input errors to the PPS are intolerable if errors in the rainfall estimates are to be kept at desirable levels.
	Clutter suppression ≥ 30 dB	X				This magnitude of clutter suppression must be achieved through signal processing in order to eliminate clutter when combined with multiple-tilt computer processing. Especially critical requirement in mountainous terrain.
Computer processing of the preprocessed signals	On-site computer hardware with PPS software as illustrated in Fig. 8	X				The required level of quantitative accuracy for hydrologic forecasting cannot be achieved without substantial real-time computer processing at the radar site. The only other alternative would be "wide-band" communications to an external computer.
Incorporation of automated rain-gage data into processing	Communication and software interfaces as illustrated in Fig. 8	X				"Ground truth" data are mandatory for accurate quantitative estimates.
Integrated system design for automated data acquisition & processing	Acquisition, preprocessing, processing, and output executed in sequential automatic stream, taking advantage of the inherent characteristics of the radar data at each step	X				All experiences in the United States and abroad dictate that NEXRAD must employ such an integrated system design to achieve the accuracy and timeliness requirements for real-time precipitation estimation applications.
Doppler channel data//////////////////////	//////////////////////	//////	//////	//////////////////////	//////////////////////	Doppler data are not considered directly in this benefit analysis; however, it is likely that use of the Doppler data will be necessary to obtain the required 30 dB of clutter suppression. Also, the use of Doppler data to assist in the assessment of the variability of the reflectivity to rainfall transformation relationships should prove valuable as future developments in this area proceed.

[1]Estimated mean percent increase in error.
[2]Estimated loss in benefits over a 20-year period.

Table 3. Calculation of the increase in the mean percent error in the precipitation estimates obtained using a 1.5° beamwidth radar instead of a 1° beamwidth radar.

RANGE INTERVAL (KM)	MEAN RATIO OF NEAR RANGE TO FAR RANGE INTENSITY 1.0°	1.5°	DEVIATION OF MEAN RATIO FROM 1.00 1.0°	1.5°	ASSUMED RESIDUAL ERROR AFTER APPLYING MEAN CORRECTION ($^1/_2$ DEV$_{1.5°}$ − $^1/_2$ DEV$_{1.0°}$)	PERCENT OF TOTAL AREA WITHIN THIS RANGE	WEIGHTED ERROR OVER THE ANNULAR AREAS (PERCENT)
0 - 140	1.00	1.00	0.00	0.00	0.0	37	0.0
140 - 170	1.00	1.06	0.00	0.06	0.03	18	≃ 0.5
170 - 200	1.07	1.23	0.07	0.23	0.08	21	≃ 1.7
200 - 230	1.28	1.61	0.28	0.61	0.165	24	≃ 4.0
					MEAN INCREASE IN ERROR OVER TOTAL AREA		≃ 6.2

benefit reduction on the high side, the percent increase in error was directly applied to the determined benefits. It was also assumed that the same percentage loss would be incurred in the savings from improved water management information.

These calculations were based on convective rainfall measurements; much greater losses would be incurred for stratiform precipitation and even greater ones for snowfall. It is important to remember that over 70 percent of the runoff in the Western States results from snowfall. Also not considered is the likelihood that a wider beamwidth, which may be accompanied by an increase in sidelobe intensities, can result in more ground clutter.

CONCLUSION — Widening of beamwidth from 1° to 1.5° will result in substantial loss in accuracy for measurement of rain beyond 150 km from the radar and an even more serious degradation of snowfall measurements. It is estimated that the total benefits lost over a 20-year period would be $1.6B.

3.2 Impact of Reducing the Dynamic Range from 93 dB to 80 dB

To arrive at an estimate of how much the accuracy in precipitation estimates might be degraded by a 13 dB reduction in dynamic range, the following points were considered: 1) as illustrated in Figure 4, approximately 50 percent of the rain water in convective storms is distributed in the heavy rain core regions occupying only 5 percent of the rain area and 2) when peak ground clutter areas coincide with these heavy rain cores, signal saturation will occur, making it impossible to accurately estimate rainfall in these core regions. If it is assumed that: 1) 25 percent of the damages from flooding is associated with these heavy rain areas (conservative in view of item 1 above), 2) alignment of such heavy rain cores with areas of peak clutter intensity occurs at only 0.2 percent of the times and locations, and 3) interpolation can be employed to recover 6 dB of the 13 dB loss in the dynamic range reduction, then the resulting average impact on rainfall estimation accuracy can be calculated as follows:

$$\Delta E = FR \cdot FA \cdot G \cdot SE,$$

where

ΔE = increase in percent error due to reduction in dynamic range,

FR = fraction of rain water in heavy rain cores,

FA = fraction of occurrences with alignment of heavy rain cores with areas of peak clutter,

G = gain factor to account for the assumption that a large percent of the flood damages, say 25 percent, are associated with the heavy rain core areas (5 percent of total storm area),

SE = percent error resulting from saturation, i.e., 7 dB expressed as percentage.

Therefore,

$$\Delta E = 0.5 \cdot 0.002 \cdot (25/5) \cdot [(10^{7/10}-1) \cdot 100]$$

$$= 0.5 \cdot 0.002 \cdot 5 \cdot 400$$

$$\Delta E = 2\%$$

This increase in error of mean precipitation estimation was then translated through the benefit analyses as was done for the beamwidth error explained in Section 3.1.

This evaluation was based on a consideration of loss in dynamic range at the upper end of the scale, where convective rainfall cores will be affected. However, lowering of the radar sensitivity will significantly impact the capability to measure snowfall at the middle and farther ranges. Another factor not considered in the evaluation is that the most critical potential loss-of-life situations, such as the Big Thompson Flood, may have a high probability of coinciding with heavy rain cores and areas of peak clutter intensity in mountainous areas.

CONCLUSION -- Reduction in dynamic range/sensitivity will cause loss of accurate measurement of some heavy rain cores on the high end of the scale and will reduce the effective range of dry snow measurement on the low end. It is estimated that the total benefits lost over a 20-year period would be $510M.

3.3 Impact of Reducing the Operational Reliability from 98.9 Percent to 96 Percent

It is not possible to accurately quantify the increase in error in precipitation estimates attributable to a 2.9 percent decrease in operational reliability, since it is not known how the increase in down-time would be distributed throughout the year. However, it is possible to estimate what the loss in economic benefits might be, by considering several factors. First, it is known that in the conterminous United States precipitation occurs on the average about 7 percent of the time when all locations and seasons are considered. Second, if we assume that the down-time is uniformly distributed throughout the year, then there would be an additional loss of precipitation estimates during 2.9 percent of the precipitation periods if the individual down-time periods exceeded about 1 hour in duration (Figure 5 illustrates the increase in error with lengthening of interval between samples). In actuality, the time distribution of the down-time intervals will probably be such that some of the intervals will be less than 1 hour, still allowing precipitation accumulations to be derived but with some loss in accuracy. Also, in practice, the down-time probably will not be uniformly distributed throughout the year. Experience has shown that outages will be correlated with severe weather and heavy rain periods. (Radar system operations are particularly susceptible to lightning activity.) The assumption made for this analysis is that these two effects will tend to offset each other and that a reasonable estimate of the loss in precipitation data will be equal to the decrease in operational reliability, i.e., 2.9 percent. Therefore, the loss in economic benefits is assumed to be 2.9 percent.

It is probable that this evaluation is conservative, since the increased losses associated with the high correlation of outages with severe weather and heavy rainfall most likely outweigh the reduced losses due to down-time intervals of less than 1 hour.

CONCLUSION -- Lowering of operational reliability will cause some complete losses in storm coverage and will lead to increases in estimation error during periods when intervals between samples are too long. It is estimated that the total benefits lost over a 20-year period would be $750M.

3.4 Discussion

The major technical requirements of the NEXRAD system relevant to obtaining accurate estimates of precipitation have been examined to determine if relaxation of any of the requirements might be cost effective. Table 2 summarizes the results of this examination. It was concluded that only three technical requirements might be relaxed. Significant relaxation of any of the other technical specifications would produce a serious degradation in the accuracy of the precipitation estimates. This is not to say that relaxation of certain NEXRAD technical requirements would render the precipitation estimates useless. However, there would be a rapid growth in precipitation errors leading to significant losses in benefits. Figure 9 shows the relationship between the loss in economic benefits and the increased error associated with additional relaxation in the NEXRAD technical specifications. The base error corresponding to zero percent reduction in accuracy on the diagram is the error in precipitation estimates from a fully equipped NEXRAD radar supported by a network of 30 automated rain gages. For this study, this base error is assumed to be equivalent to the error from 300 rain gages distributed so as to measure rainfall over the same area as the radar. For example, the average percent base error for a 7500 sq mi basin (the basin size associated with the centroid of the economic benefits distribution given in Table 4 in Section 4.2.2) is estimated to be about 15 percent.

As illustrated in Figure 9, when the error is such that the reduction in accuracy is around 25 percent, an accelerated increase in runoff forecast errors is apparent due to the magnification of the input errors as they proceed through the runoff process (see Figure 1). When the increase in error due to specification relaxation reaches about 50 percent, the NEXRAD precipitation estimation capability is degraded to a level where automatic acquisition and processing, as illustrated in Figure 8, becomes infeasible.

A wealth of experience in this country and abroad has demonstrated that a sound, integrated system design is required if quantitative precipitation estimates suitable for real-time hydrologic forecasting are to be obtained from weather radar measurements. Any weak link in the system will negate the feasibility of application of this weather radar technology. Loss of such an opportunity would translate to a very large loss in economic benefits to the Nation.

Each of the three technical requirements selected for possible relaxation was evaluated to determine how much loss in accuracy in the precipitation estimates would result from the less stringent specification, and how this loss in accuracy would impact the estimated economic benefits. In all three cases, the estimated loss in benefits, over a 20-year life cycle for NEXRAD, far exceeds the capital costs of implementing the more stringent requirements. And, in each case, it is believed that these loss-in-benefit estimates are conservative.

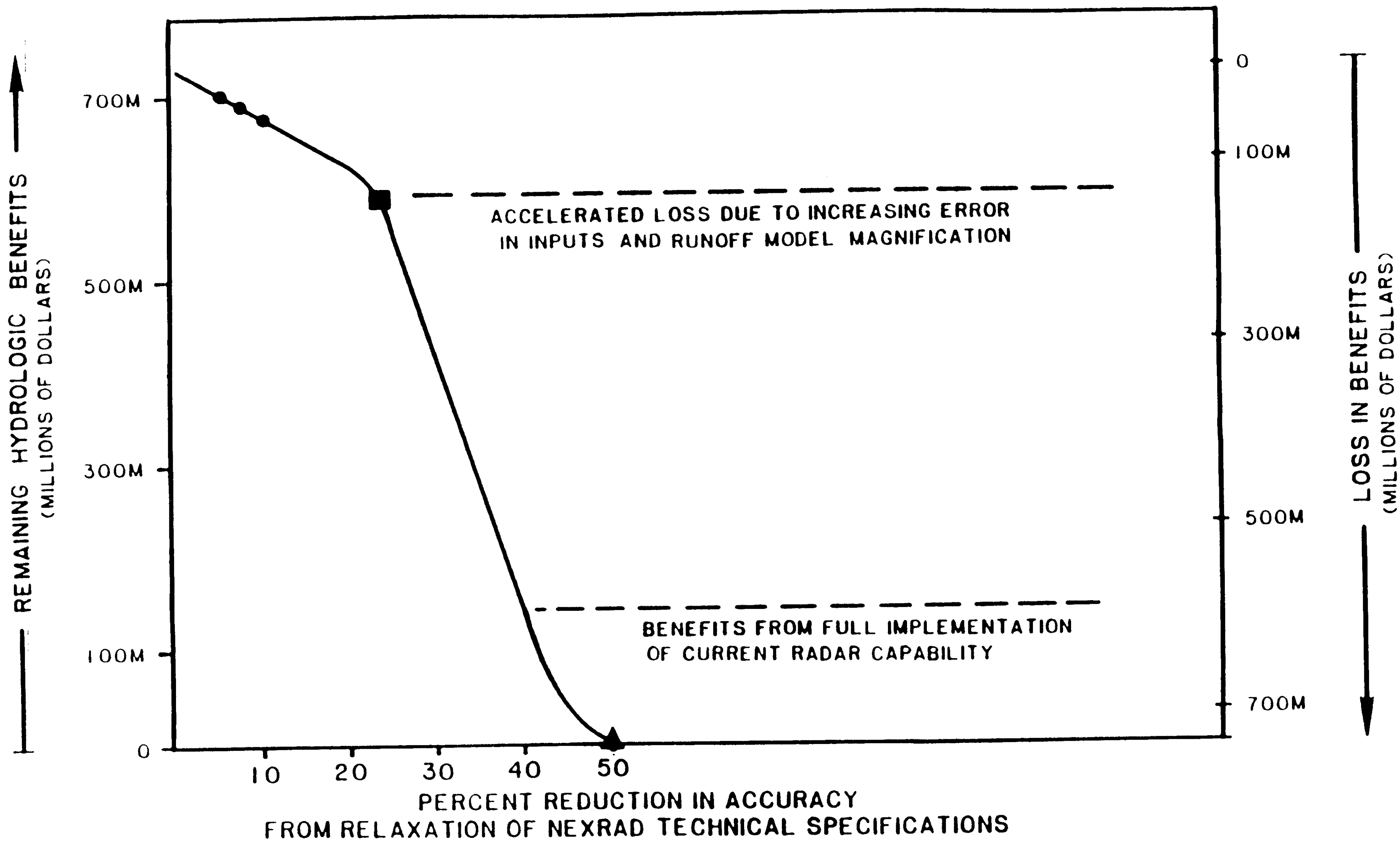


Figure 9. The curve relates the loss in benefits to the reduction in accuracy (increase in errors in precip estimates) with relaxation of the NEXRAD technical specifications. Dots (●) on the upper end of the curve represent losses in Table 2 associated with changes in the specifications for beamwidth, dynamic range, and system reliability. The solid box (■) is the point at which increasing precipitation input errors cause an accelerated increase in runoff forecast errors due to magnification of the input errors as they progress through the runoff process (see Figure 1). The triangle (▲) is the point at which the NEXRAD precipitation estimation capability is degraded to a level where automatic acquisition and processing, as indicated in Figure 8, becomes infeasible.

4. BENEFIT ANALYSES

As described in Section 1, the benefit analyses will consider two significant applications in the hydrologic area where economic benefits will be realized from a radar network conforming to the technical requirements planned for NEXRAD. The assumptions made to develop the benefit model and analyses, and significant intermediate results, will be presented.

4.1 Hydrologic Areas Where Economic Effects Will Be Realized

The two primary areas of benefits from improved precipitation estimates that will be considered in the analyses are: reduced flood damages, and improved water management information (resulting in increased water and power yields and deferred construction costs).

Damages due to flooding are now between $3B and $5B annually, and are increasing (Figure 10). There appears to be an increase in the slope of the curve for the most recent years, so an extrapolated value for the year 2000 (the mid-point of a 20-year NEXRAD life cycle) would be $6-12B and by the end of the 20-year period, in the year 2010, damages would be in the range of $9-25B in 1983 dollars. Increases are related to demographic trends which bring pressure for more development in flood plains. Reduction of this damage by a few percent would lead to the saving of hundreds of millions of dollars. The benefits will result from an increase in both the warning lead time given to occupants of areas at risk to flooding, and the accuracy of the forecast. The accuracy is evident in both a better estimate of the flood crest, and in a better estimate of the timing of the flood wave. The increase in accuracy will have a directly measurable effect which is modeled in the analyses but also will have a significant impact (which is difficult to measure) because of the greater confidence the using public will develop as a result of the increased accuracy.

The second area of economic benefit will be improved management of water. For the maintenance of an adequate supply of water for community water consumption, power generation, industry, agriculture, navigation, recreation, fish and wildlife development, and sanitation, water must be controlled so that required amounts are available in the quantity and of the quality desired. Improved management of water resources, as water supplies become more critical in the future, will depend on timely and accurate hydrologic forecasts which, in turn, will depend on high quality precipitation inputs.

4.2 Flood-Loss Reduction Benefit Model

4.2.1 Flood forecast benefits

The primary economic benefit of a flood warning system comes from the reaction time given to occupants of areas at risk to flooding so they can take actions which will reduce their losses. Both the expected time at which flooding will begin and the extent (depth) to which flooding will occur are required so that appropriate action can be taken to reduce flood losses. Overforecasting causes problems which are significant, though different from those associated with underforecasting. For example, costs for emergency

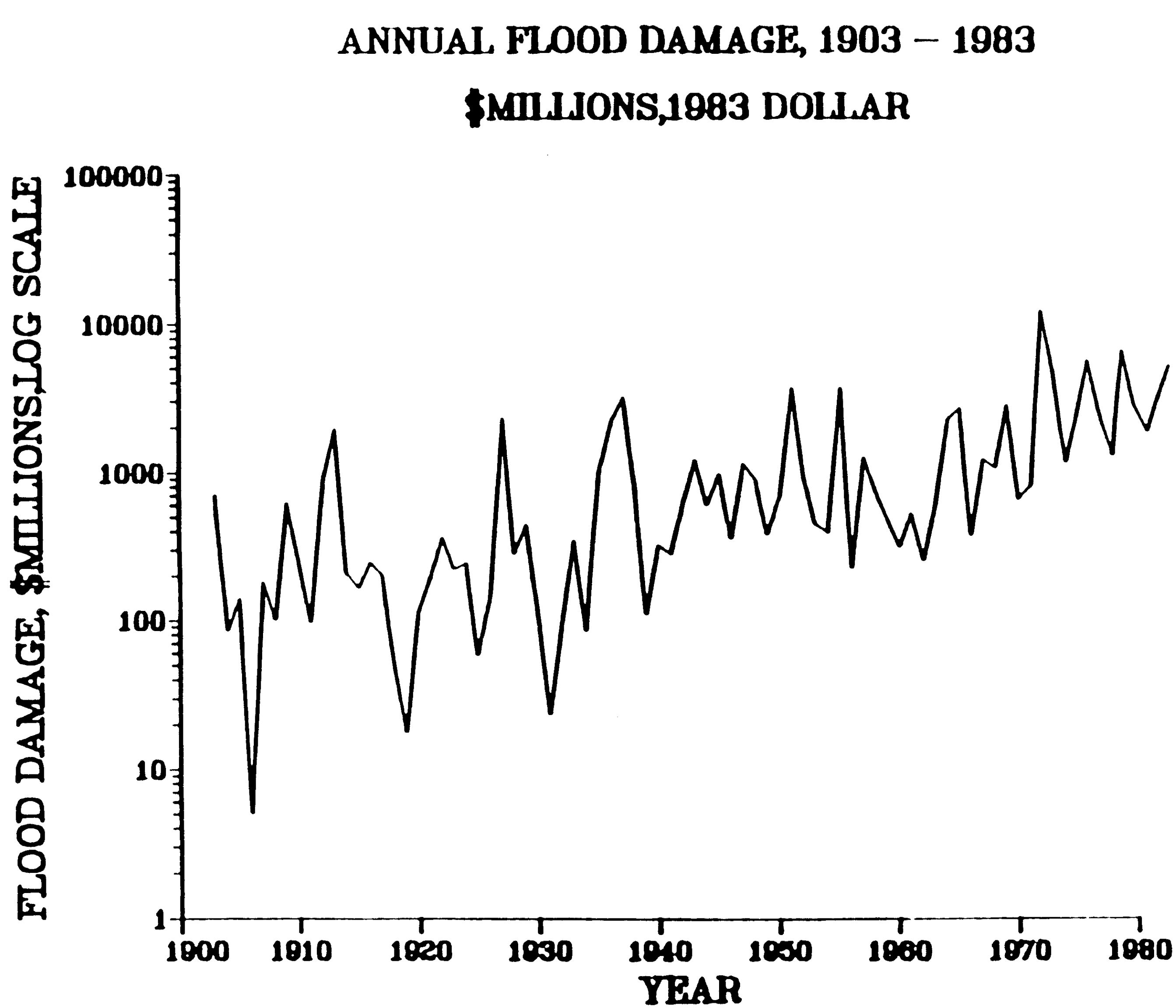


Figure 10. Historical trend in nationwide flood damages (in 1983 dollars) [NWS-OH, 1983].

actions that are unnecessarily taken are losses just as much as costs due to damage from the high water itself. In the same vein, actions which are futile because of inadequate time (such as attempting to build levees which are washed away before they can be completed) generally result in greater losses than would have occurred if those actions had not been taken. Improvements in the warning system are best measured in terms of an increase in the warning or Forecast Lead Time (FLT). The Maximum Potential FLT (MPFLT) is the length of time between the time when significant precipitation begins to fall and the time at which flooding begins at the forecast point. This time interval is similar to the basin lag time (T), the interval separating the time when one-half of the precipitation has fallen and the time of the passage of the center of mass of the runoff past the forecast point. While the MPFLT and the T are slightly different, their similarity is strong enough that we will consider them to be equal. Both are dependent on the size of the basin, with bigger basins having longer T's than smaller basins. For any given storm, some significant portion of the storm must be sampled before the crest can be forecast. Time is also required to collect the data from the sensors in the field, to process the rainfall reports through a hydrologic runoff model, and to disseminate the forecast. The longer any one of these processes take, the shorter the FLT will be. Conversely, any hope for lengthening the FLT is found in the shortening of these processes. Because precipitation, especially intense rainfall, generally is extremely variable in time and space, it is difficult to make accurate assessments of the effective average precipitation falling on a basin. The accuracy of the precipitation amount plays an important part in the accuracy of the forecast. The accuracy with which the average precipitation can be estimated affects the value of the warning to the user. To represent this effect, a theoretically derived penalty is used in the computation of the benefits associated with the FLT.

The errors attributable to the hydrologic model are assumed to be constant in the analyses. This assumption tends to make the benefit analyses more conservative, since reduced error in the input data will probably encourage improvements in model development and ultimately give greater accuracy, with associated additional benefits in the resulting performance.

In the analysis below, the FLT is based on basin size. The sampling period that is used in the computation is one quarter of the basin lag time or T/4. This interval is used because it represents an upper limit to the time interval that most forecasters would be willing to wait before issuing an initial forecast. In many cases storms will not remain over a basin as long as T/4, and significantly shorter times than T/4 may be used.

In this respect the model takes the worst or most conservative case to develop the FLT and associated benefits since, for shorter storms on basins of moderate size, the effective sampling time would be less than T/4 and longer lead times could be achieved. Any increase in the FLT is used with the damage reduction curve shown in Figure 11 to estimate the economic benefits due to improvements in the forecast system. Comparisons are drawn between the benefits obtained from the NEXRAD system, supported with a small number of automated rain gages, and the benefits derived from a network of operational rain gages. [The plan for the supporting automated gages was described in a Program Development Plan to Improve Hydrologic Services (NWS-OH, 1982).]

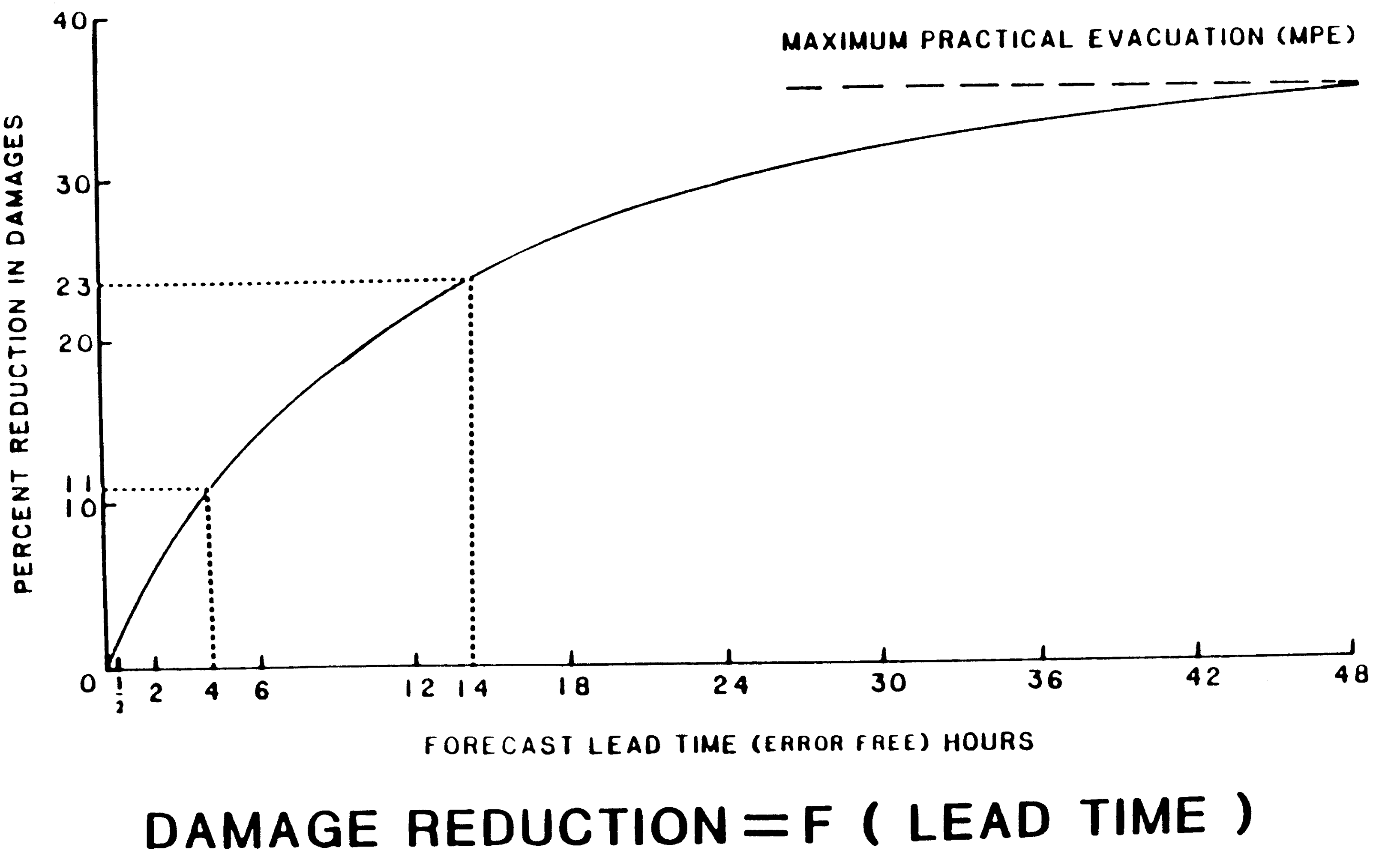


Figure 11. Potential flood damage reduction made possible by a given response time (accurate forecast lead time). The dotted lines in the figure give an example which shows that as the forecast lead time increases from 4 to 14 hours, the additional response time raises the percent reduction in damages from 11 to 23 percent (Day, 1970).

The model is based upon the following assumptions.

1) With respect to accuracy of hourly totals of precipitation on basins of several hundred km^2, a radar calibrated by 30 gages per radar umbrella is equivalent to 300 rain gages without radar over the same area. (See Figure 12.) This result was derived from a study done by W.F. Krajewski using methods described by Krajewski and Georgakakos (1984) and Krajewski and Hudlow (1983, 1984). This number is considered conservative, since other studies have suggested that an even larger number of gages would be required to be equivalent in accuracy to a radar calibrated with a few gages. [For example, Bussell et al. (1978) report that a radar calibrated by 1 gage per 1000 km^2 is equivalent to a gage only density as high as 35 gages per 1000 km^2.] For a radar to be capable of the accuracy required for the factor of ten equivalency or better (radar plus 30 gages versus 300 gages), it should have specifications at least equivalent to those planned for NEXRAD and described in Section 2.

2) A network of 30 gages is used to adjust the precipitation estimates at each NEXRAD site.

3) Without NEXRAD, precipitation would be measured using 30 automated gages reporting hourly, 10 additional 6-hourly reporting first-order observer gages, and 20 additional daily reporting cooperative observer gages per NEXRAD coverage area.

4) The reliability of reports (percent of the time reports are received on time) is assumed to be 90 percent for all gages and for the radar adjusted precipitation measurements.

5) The time required to acquire all data, prepare the streamflow forecast, and disseminate the forecast is set to 1 hour for both the gage only and the gage adjusted radar cases.

6) Data from the hourly reporting gages are available for acquisition 1 hour after the precipitation event begins. For radar, this time is 15 minutes.

7) The catchment lag time (hours) is a function solely of the catchment area (square miles) according to the equation

$$T = 1.29A^{0.428} ,$$

which is based on basin responses to rainstorms in the Ohio and Mississippi River basins, and on basins in Puerto Rico.

8) The forecast is made after time T/4 has passed or after the sampling interval has passed, whichever is greater.

9) Forecast Lead Time (error free) is computed as

$$\text{FLT} = [\text{MIN } (3/4\ T,\ T - (\text{Sampling Interval})) - 1\text{ hour}].$$

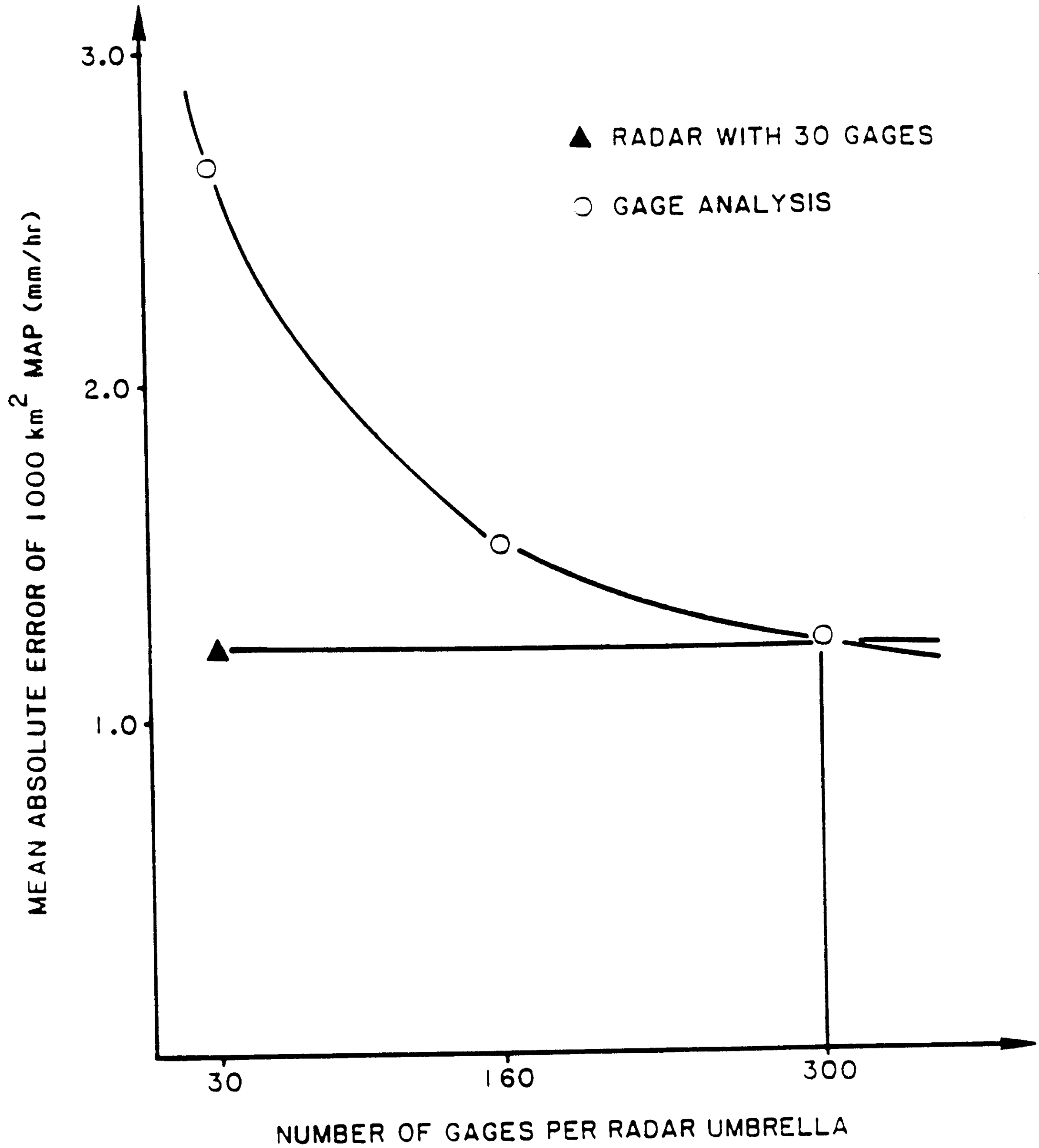


Figure 12. The error in precipitation estimates is shown as a function of the number of gages per radar umbrella (166,190 km^2). The triangle (▲) indicates the error in the radar estimates (adjusted with 30 gages) to be approximately the same as that for 300 gages without radar.

10) Damage reduction (error free) is computed, based on Figure 11.

11) Damage Reduction Penalty due to errors in the forecast caused by errors in the mean areal precipitation (MAP) estimates is computed according to:

Penalty = 100 percent for $CV \geq 0.5$

or

= $2 \times CV$ for $CV < 0.5$

where CV is the coefficient of variation of error in MAP.

CV is computed from an empirical equation derived from data collected in the Muskingum River basin in Ohio as follows (Schaake, 1978):

$$CV = 0.082 S^{-0.22} A^{-0.302} G_E^{-0.602}$$

where

S = Sampling interval (hr)
A = Basin area (sq mi)
G_E = Effective density (gages/sq mi)

12) Total U.S. damages are spread uniformly over catchments on a per unit area basis.

In assumption (3) above, a ratio of first-order stations (which report every six hours) to cooperative stations (which usually report on a daily basis) was given as 10 first order stations to 20 cooperative stations. This suggests far fewer than the actual number of cooperative stations. The ratio of physically existing gages is approximately 10 first-order stations to 60 cooperative stations. The 10/20 ratio was chosen because in most areas of the country up to 80 percent of the cooperative stations do not report unless they have received 0.5 inches of rain during the 24 hours preceding their normal daily observation time. When heavy rain is observed, the observers are requested to continue to report every six hours until the intense rain ceases. Field reports suggest that a significant percentage of these stations do not report at other than their primary observation times even when such reports are merited. In the benefit analysis model a simplifying assumption was made that all stations report at 90 percent reliability. To compensate for the lower reliability and the reporting criterion of the cooperative stations, a 10/20 ratio was assumed.

The planned operational reliability of NEXRAD is 98.9 percent. The lower reliability of the gages used to adjust the radar estimates and of the communications system may reduce the overall reliability of the system to 90 percent. Any additional reduction of the reliability of the radar could reduce the overall merged data reports to a reliability of less than 90 percent. In actuality, it is hoped that the NEXRAD system and its supporting automated rain gages will ultimately reach an operational reliability of over 90 percent. Conversely, the operational rain gage network, with its assorted types of gages, may never reach a reliability of 90 percent. As a simplifying assumption, for the purposes of this analysis, it seemed reasonable to assume a 90 percent operational reliability for both the radar and the gage networks.

4.2.2 Computational procedures for the flood benefit analysis model

To make comparisons, basin sizes ranging from 3 to 15,000 square miles are considered. The following procedure is then used.

Primary Input:

BASIN AREA IN SQ MI (A)

Step 1
Determine Lag Time T.

$$\text{CATCHMENT LAG TIME} = T = 1.29\ A^{0.428}$$

Step 2
Determine a reasonable sampling time for a storm scaled to the basin response time. Assume T/4 and round to the next higher multiple of observation times (i.e., sampling time of 1.5 hours would have to be rounded to two hours if data are observed hourly).

Step 3
Compute Forecast Lead Time (FLT) for each possible observation time (i.e. one FLT for the radar, one for the hourly gages, one for the gages with a 6-hour reporting schedule, and one for the gages which report daily). Six-hourly reports would include all of the hourly reports, and daily reports would include all gage reports.

Step 4
Look up the percent of damage reduction corresponding to each FLT using the curve in Figure 11.

Step 5
Reduce the potential benefits obtainable from improved precipitation measurements by the fraction of the benefits attributable to streamflow information as indicated in Figure 13.

Step 6
Compute penalty due to the error in the estimate of the mean basin rainfall as explained in assumption 12.

Step 7
Reduce the percent damage reduction by the penalty induced by the uncertainty in the rainfall data.

This now gives a percent damage reduction estimate for each basin size, for the radar system, and for each type of observation (hourly, 6-hourly, and daily) from rain gage reports where the CV is less than 0.5.

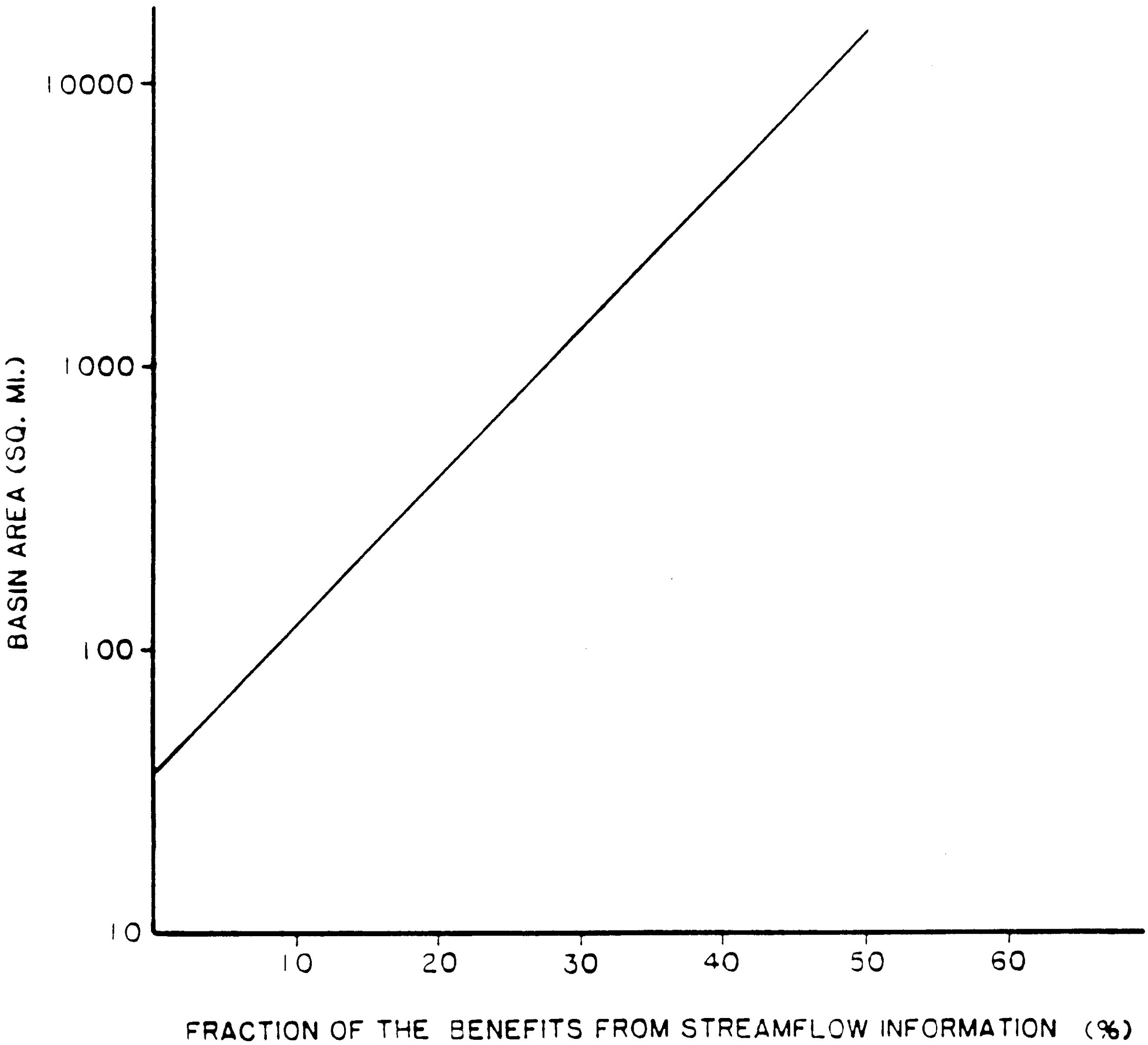


Figure 13. Curve showing the relationship (assumed in benefit model) between basin size and the fraction of total benefits occurring from streamflow (stage and discharge) information. The model attributes the remaining fraction of benefits to precipitation information.

Step 8

For each size basin, select (from the damage reduction estimates based on gage only observations) the largest reduction estimate and subtract it from the corresponding radar system damage reduction. This difference is the NEXRAD benefit for the basin size. Where a radar system benefit exists, but because of large CV's no positive benefit exists for this size class from gage observations alone, the radar benefit is the net benefit.

Step 9

Determine the percent of the total area of the country that corresponds to each basin size class. Compute the current total annual flood loss for each class of basin size according to the percent of the total area for each class, assuming $5B in total damages for the whole country. (See Figure 10.) The percent of basins of each size class was taken from a report written for the NWS by GKY associates (GKY, 1981). (See Table 4.)

Step 10

Determine the average improvement in each basin size class by taking the arithmetic average of the NEXRAD benefits of the two class end points. For example, for basins 1,000 sq mi in area, the difference in damage reduction is 12.5 percent; for 5,000 sq mi the difference is 6.7 percent. The mean improvement for basins from 1,000 sq mi to 5,000 sq mi is assumed to be (12.5 + 6.7)/2 = 9.6 percent. (See Table 5.)

Step 11

Multiply the percent improvement (NEXRAD system vs. rain-gage system) for each basin size class by the annual damage for those basin size classes (from Table 4), and sum the results. (See Table 5.) This sum is the difference in dollar benefits between the gage only and the NEXRAD-gage systems. Divide this sum by the total annual flood damage to derive the benefit in terms of percent of the annual flood loss (i.e., 4.8 percent).

The total flood damage reduction benefits for a 20-year life of the NEXRAD systems may be estimated by the following steps. Assume a linear increase in both damages and potential damage reduction over a 20-year period. Figure 10 was used to estimate damage in the range of $6-12B for the year 2000 (the midpoint of the period). Therefore, $9B was taken as an average for the life of the NEXRAD system. The percent damage reduction (4.8 percent) multiplied by $9B multiplied by 20 years gives the total benefits attributed to flood damage reductions for the life cycle of the NEXRAD network.

CONCLUSION — The flood damage reduction benefits provided by an optimal radar such as NEXRAD would be, on the average, 4.8 percent of the annual flood damage, or roughly $245M per year in the current year. As the damage potential mounts as suggested by Figure 10, this number would increase. The increase in flood damages is assumed to be linear with time. As noted earlier, the losses in the year 2000, at the mid point of a 20-year life cycle of NEXRAD, are anticipated to be about $9B per year. At 4.8 percent of the total yearly loss, the mean annual benefit for a 20-year life cycle would be $432M. The total estimated benefits from reduced flood damages over the projected life cycle (20 years) of the NEXRAD network is about $8.6B (in 1983 dollars).

Table 4. Projected annual damage from flood losses for 1984 by classes of basin size.

BASIN AREA (sq mi)	FRACTION OF TOTAL AREA	ANNUAL DAMAGE IN AREA CLASSES (millions of 1983 dollars)
0 - 25	0.00124	6.2
25 - 50	0.00074	3.7
50 - 125	0.00349	17.5
125 - 200	0.00646	32.3
200 - 400	0.0119	59.5
400 - 625	0.0102	51.0
625 - 800	0.00842	42.1
800 - 1000	0.00711	35.6
1000 - 5000	0.119	595.
5000 - 10000	0.237	1,190.
10000 - 15000	0.396	1,980.
>15000	0.198	990.

Table 5. Incremental flood damage reduction by basin size expected from the improved precipitation estimates of NEXRAD. (Values are based on flood damage projections for 1984.)

BASIN AREA (sq mi)	PERCENT DAMAGE REDUCTION	INCREMENTAL DAMAGE REDUCTION (millions of 1983 dollars)
3 - 125	0.0	0.0
125 - 200	3.4	1.1
200 - 400	6.2	3.7
400 - 625	9.2	4.6
625 - 800	11.1	4.6
800 - 1000	12.2	4.3
1000 - 5000	9.6	57.1
5000 - 10000	5.4	64.3
10000 - 15000	5.3	104.9
		Total ~ 245

4.3 Water Management Information Benefit Analyses

The benefits from improved water management are attributable to:

1) Improved efficiencies which allow deferred or reduced expenditures for control structures and sewage treatment and control facilities.

2) Additional water available for agriculture, public water supply, and industry.

3) More efficient farm management based on more accurate water supply assessments.

4) Greater production of hydroelectric power with existing facilities.

5) Benefits to navigation.

6) More effective use of recreational facilities and wildlife habitats.

The present value of existing control structures has been set at $170B. It seems reasonable that current population pressures and industrial growth will stimulate additional building, annually equal to 0.5 percent of the current value (NWS-OH, 1982). The annual expenditures required for such increases would be $8.5B. New advances in hydrologic technology are estimated to have the potential to increase the efficiency of all structural systems in the range of 5-15 percent. Taking the lower figure (5 percent) as a conservative estimate of the reduction in building that will occur because of the improved efficiency, and making the reasonable assumption that at least half of the improvement in efficiency results from greater accuracy in the hydrologic inputs (primarily precipitation), we can assign a benefit to the data gathering system (NEXRAD) of $212M (2.5 percent of the $8.5B). Examples are given in the following two paragraphs to substantiate this premise.

Smith et al. (1982) reported that operation of reservoirs on the Potomac River using techniques developed in cooperation with the Potomac River Basin Commission, the Office of Water Research and Technology, the U.S. Army Corps of Engineers, and the NWS produced an effective increase of between 100 and 200 percent in the water yield of existing reservoirs. In this case alone, improved operations, costing less than one-half of one percent of projected construction costs, eliminated the need for up to $0.25B of additional reservoir construction. The estimate is based on the assumption that benefits are proportional to replacement value of planned construction.

An American Society of Civil Engineers workshop on reservoir systems operations in 1979 reported several additional examples of potential benefits resulting from improved hydrologic forecasting:

1) A 10 percent increase in the value of power from the California Central Valley Project.

2) Up to a 20 percent increase in the value of power from TVA facilities.

3) A three to six percent increase in flood reduction and navigation benefits in the Arkansas River Basin.

4) A 50 to 60 percent reduction in flood flows while increasing energy production in the Colorado River Basin.

The value of improved water management decisions depends on the use of the additional water yields. An Office of Technology Assessment report on water-related technologies (OTA, 1983) gives ranges of site specific values of water for Western U.S. use as:

Consumptive use:
- Agriculture.................... $7 to $80/acre ft
- Industry....................... $0 to $1,600/acre ft
- Domestic use................... $150 to $250/acre ft

Nonconsumptive use:
- Hydropower generation......... $3.30 to $30/acre ft
- Waste load dilution........... $1.30 to $15/acre ft
- Recreation.................... $2 to $13/acre ft
- Fish habitat.................. less than $1/acre ft

The range of values per acre foot reflects the range of water availability throughout the Western States and the local source of the water. In some areas of the Southwest, groundwater costs on the order of ten times more per acre foot than water from reservoirs behind large government built and operated dams. The cost of the dams and their operation generally is paid by taxpayers throughout the country. Thus, although users of reservoir water pay part of the cost of their water, they are partly subsidized by other taxpayers. If the true cost of the water was calculated, the effective lower limit on costs would increase as would the mean value of the water.

The enormous amounts of water used in these areas at these costs per acre foot have significant economic impact in the region. Changes of only a few percent in the amount of water available, or in the efficiency with which the water is made available, result in large dollar benefits.

For agricultural irrigation, it has been estimated that a six percent improvement in forecast accuracy would result in increased returns ranging in value from $0.32 to $12.33 per acre of land irrigated using surface water. The benefits are highest in the Colorado Basin and lowest in the Pacific Northwest (Castruccio et al., 1981).

The economic benefits (resulting from improved forecasts) in the management of water for hydroelectric power generation are estimated at from $0.03 to $1.03 per megawatt of power generated. The total annual benefits in the Western States for a six percent improvement in forecasts for irrigation and hydropower are $36.5M (Castruccio et al., 1981). To extrapolate these benefits to the whole country in 1984 dollars, the following assumptions were made. 1) Forecast improvements of up to 25 percent are potentially available (Lettenmaier et al., 1980); however, improvements of around 10 percent are the expected average (OTA,1983). 2) A linear increase in benefits is assumed to occur for a unit increase in forecast accuracy, so that a 10 percent improvement would be 10/6 times the $36.5M in 1981 dollars. 3) There has been roughly a 10 percent inflation between 1981 and 1984. 4) Electricity rates in the Eastern US are as much as 30 percent higher than in the Pacific Northwest, and could average around 20 percent more. 5) Irrigation, once almost exclusively limited to the 11 Western States, is now extensively used in much of the Midwest and South. Hydroelectric power generation is also receiving greater emphasis in all parts of the country. The overall water mangagement improvement in the remainder of the country, which includes the megalopolis of the Northeast, just equals that estimated for the Western States. Given these assumptions, the benefits for the whole country from irrigation and hydroelectric power alone would total $146M per year, of which we estimate that one-half, or $73M, can be attributed to the improvements provided by NEXRAD.

In addition to benefits to agriculture from improvements in irrigation management, there is a benefit of about $10 per acre (reported by Nelson, 1969) to farmers and stockmen who take advantage of water supply forecasts in farm management. Since there are over 23M acres under cultivation in the Western States and there has been at least 100% inflation between 1969 and 1983, the total potential benefit from use of water supply forecasts is at least $460M. A University of Nebraska study (BuREC, 1969) suggests that for every $1 increase in net crop production there is a $6.5 increase in new business, yielding a potential economic benefit to the community of approximately $3B. If an additional 10% of the total 23M acres were brought under water management, there would be an incremental benefit of $300M. Since this benefit is dependent on an accurate water supply forecast, it seems justifiable to attribute one-half of the improvement, or $150M, to improved precipitation estimates, hence to NEXRAD.

For navigation interests, knowledge of the river stage along navigable rivers is essential to the planning of loading of commodities onto barges and the scheduling of traffic. For example, according to the Sioux City Barge Line, for every 0.1 foot change of river stage that is forecast, an additional $1,500 in commodities can be loaded onto one barge. One tugboat can tow 12 barges, and hundreds of tugboats are traversing the Nation's waterways each day. As another example, consider that in order to properly load oil tankers in the Middle East, oil companies must know the minimum river stage in the Lower Mississippi River 2 to 3 weeks in advance. The river stage information is critical to the efficient transfer of crude oil destined for the Mississippi River and interior refineries. The benefits accruing to navigation interests because of improved forecasts are difficult to summarize into a single dollar figure because they are enjoyed by many different users. However, the US Army Corps of Engineers spends $1B per year directly in maintaining and operating the navigable waterways. If the total incremental benefit to the country provided by improved forecasts for navigation was just 0.4 percent of this value, it would amount to $4M annually. Using the same assumption made for other applications, that half of the total amount can be attributed to improved precipitation estimates, the NEXRAD-related benefits would be $2M per year or $40M over a 20-year life cycle of the NEXRAD system. While this value is heavily based on reasonable suppositions, it is quite apparent that the assigned benefit is a conservative estimate, since water borne freighting is acknowledged as the cheapest form of transportation available, and the improved efficiency represents an increment of additional profit to industries which use it, with an additional benefit of lower consumption of petroleum products per transported ton-mile.

There are several other areas of application for which total benefits were not available. Ranges of water value per acre foot were given for several of these applications earlier in this section. In the light of estimates which have been based, at least in part, on actual field reports, some other significant applications are estimated as follows:

Domestic	$50M Total	$25M from NEXRAD
Industry	$40M Total	$20M from NEXRAD
Recreation, wildlife, and sewage dilution	$ 8M Total	$ 4M from NEXRAD

All of the benefits considered in this section are attributable to improved water management information. A significant fraction of these benefits, but not all, could have been classified under improved reservoir operations. The method of operation of control structures on reservoirs often involves a compromise among various interests such as flood control, public water supply, industry, irrigation, recreation, wildlife, hydroelectric power, and navigation. The potential benefits in these areas are all quite large. Only by having adequate, reliable, and timely information can the composite benefit be maximized for all of these interests.

<u>CONCLUSION</u> — The increase in benefits in the water management area alone, resulting from the increase in the accuracy of estimating precipitation that can be expected from a system with the specifications of NEXRAD, has been conservatively estimated for 1984 at $485M in 1983 dollars. This current year total estimate is composed of the following potential benefits: $212M from the deferred cost of new construction for all water uses based on more efficient operation of current systems, $73M from improved water yields for hydroelectric power and irrigation, $150M from improved agricultural practices, $2M from navigation interests, $25M from improvements in domestic water supply, $20M from industry, and $4M from all other areas including recreation and wildlife. The increase in efficiency is made possible by better short- and long-term hydrologic forecasts based on the increased accuracy of the precipitation estimates used as the primary inputs to forecast models.

4.4 Discussion of Benefits

Potential benefits of over $729M in 1983 dollars from flood-loss reduction and improved water management applications have been identified for the current year. The models and assumptions used in calculating these benefit values tended toward the more conservative value whenever a range of values or an option in the mode of computation presented itself. Total potential benefits for the 20-year period from 1990 to 2010 are estimated at $25.7B. A breakdown of the improvements by major hydrologic activity and by period is given in Table 6.

Other benefits, for which no dollar amounts were estimated, will appear in the form of greater public confidence in flood warnings leading to greater cooperation during the implementation of damage reduction measures, better data for resolving legal conflicts over water issues, less conflict between user interests arising from overallocation of water resources, and a greater degree of satisfaction on the part of the taxpayers, attributable to improved services. Also there will be additional benefits to hydrometeorological applications from improved precipitation estimates. These benefits are less

Table 6. A: Expected benefits (1983 dollars) from improved estimates of precipitation used as inputs to hydrologic forecast models as a result of the planned performance of the NEXRAD system.
B: Estimated benefit reductions attributable to relaxation of specifications for the NEXRAD system.

A: POTENTIAL BENEFITS

	1984	MEAN ANNUAL* (or benefit for year 2000)	SYSTEM LIFE* CYCLE (20-year period 1990-2010)
FLOOD DAMAGE REDUCTION	245M	432M	8.6B
WATER MANAGEMENT INFORMATION	485M	853M	17.1B
TOTAL	729M	1285M	25.7B

B: POTENTIAL BENEFIT REDUCTIONS (See Section 3 and Figure 9)

	1984	MEAN ANNUAL (or reduction for year 2000)	SYSTEM LIFE CYCLE (20-year period 1990-2010)
BEAMWIDTH BROADENING	45.2M	79.7M	1.6B
DYNAMIC RANGE REDUCTION	14.5M	25.7M	0.51B
OPERATIONAL RELIABILITY REDUCTION	21.0M	37.3M	0.75B

*Values in these columns are based on extrapolation of the historical trend in flood damages shown in Figure 10. Benefits due to damage reduction and improved water management information are assumed to have the same relative increase.

direct and more difficult to quantify. For instance, a potentially very large benefit may result from the feedback coming from improved capabilities of meteorological prediction of precipitation and temperature on the mesoscale, which in turn would improve hydrologic prediction skill and lead time, especially on basins of small to intermediate size.

The possibility of reducing capital outlay by relaxing specifications was examined. Only three specifications were identified for which some relaxation could be made without a substantial loss in the accuracy of the precipitation estimates for quantitative hydrologic forecasting. The reduction in benefits associated with the relaxation of these three NEXRAD specifications was computed. These losses (shown in Table 6) far exceed the cost of implementation. Figure 9 illustrates this loss in economic benefits as the accuracy of the estimates are reduced (errors increased) with the degradation of the specifications for the NEXRAD system. As discussed in Section 3.4, when the accuracy of the precipitation input is degraded beyond a certain point, i.e., around 50 percent, automatic use of these data becomes infeasible, resulting in a nearly total loss of economic benefits.

Finally, the results from the benefit analyses presented in this paper are graphically summarized in Figure 14. In the figure, the current year (1984) potential benefits of the NEXRAD system for flood forecast and water management applications are accumulated. Also displayed are the total overall benefits anticipated from improvements in hydrologic forecasts. It can be seen that the high quality NEXRAD precipitation estimation capability is expected to account for a large portion of the overall increase in benefits from hydrologic forecasting improvements. From an economic standpoint, implementation of a fully equipped NEXRAD network, including the Precipitation Processing Subsystem, is one of the most important elements required to improve hydrologic services in this country. The expected benefits directly resulting from the implementation of this capability are extensive, as has been demonstrated here. The need for this capability appears to be clearly justified.

The primary reason that weather radar rainfall estimates are not yet being used operationally for hydrologic forecasting in the Unites States is that no system has been designed, funded, and built to date with all of the requisite integrated design features. Implementation of the NEXRAD design, including the Precipitation Processing Subsystem, will overcome this serious deficiency.

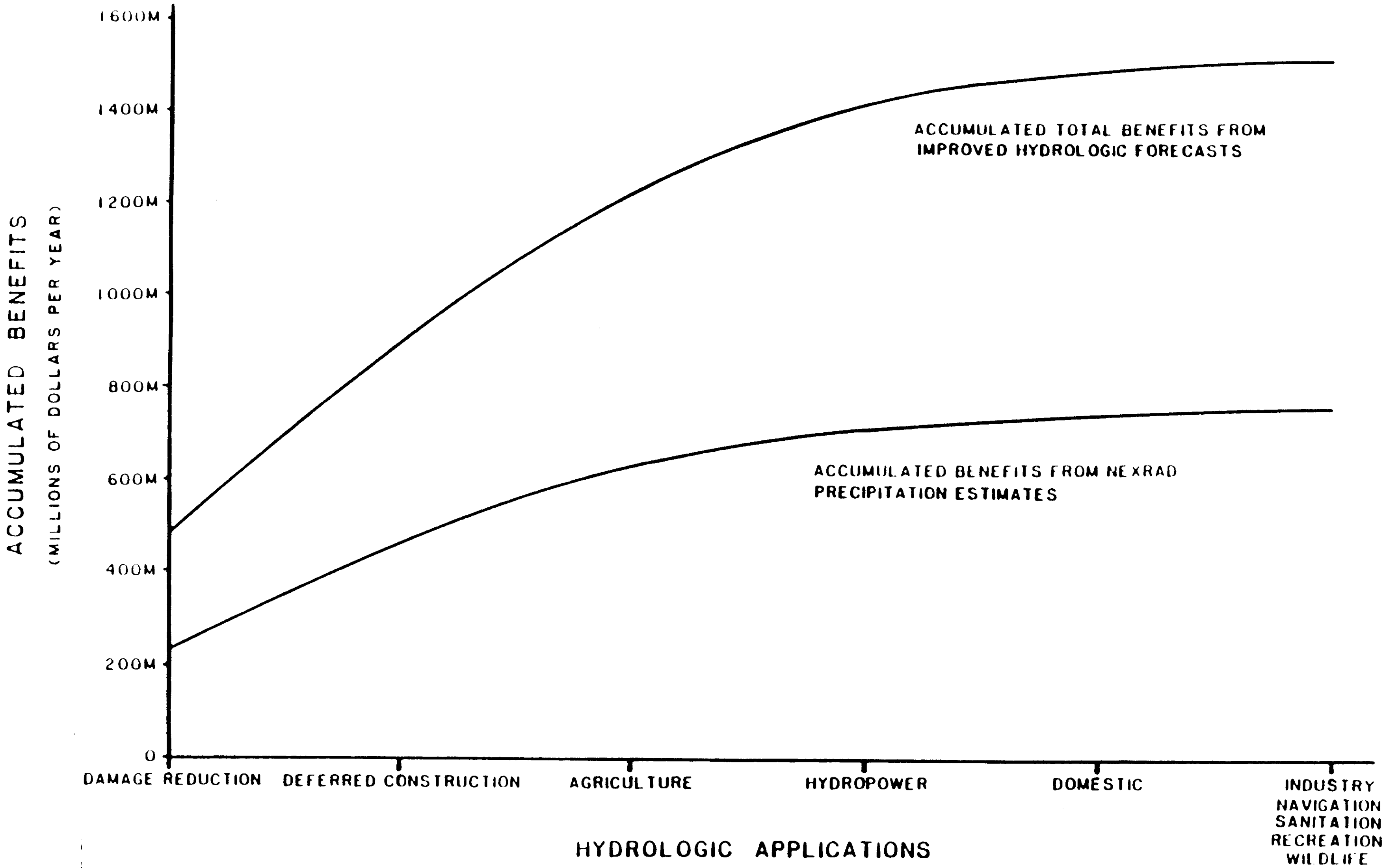


Figure 14. Estimated economic benefits associated with major hydrologic applications derived from the various improvements in the NWS hydrologic forecast system. The upper curve represents the total benefits for the various applications. The lower curve shows the fraction of the estimated benefits attributable to NEXRAD. The first application on the extreme left of the horizontal axis is flood damage reduction. The remainder of the applications are associated with benefits gained from improved water management information.

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